

Past and Present Experiments of Geo Neutrinos

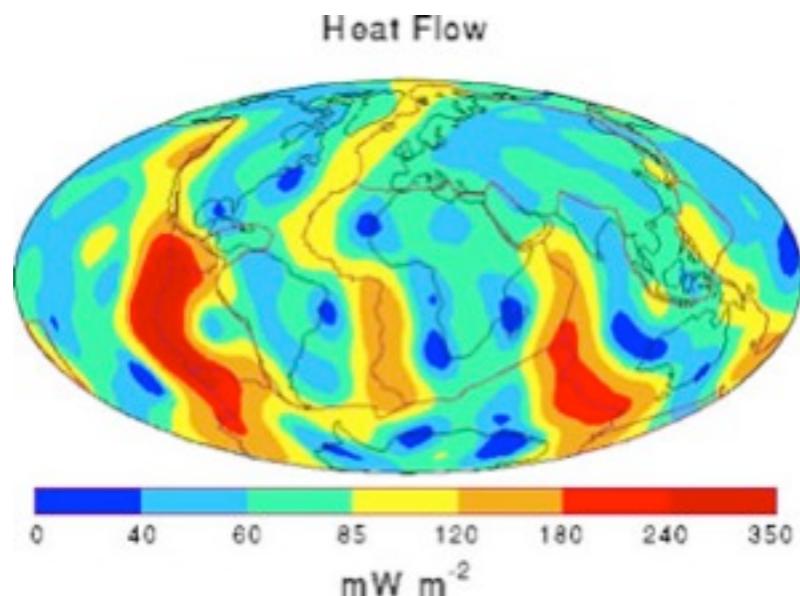
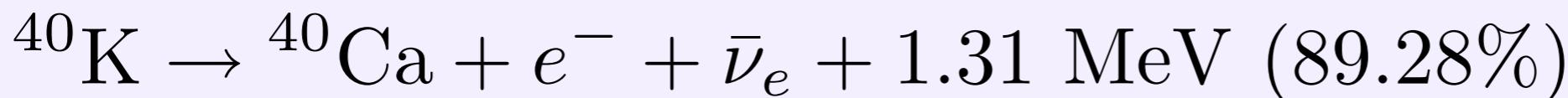
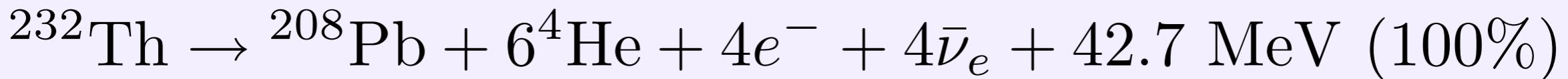
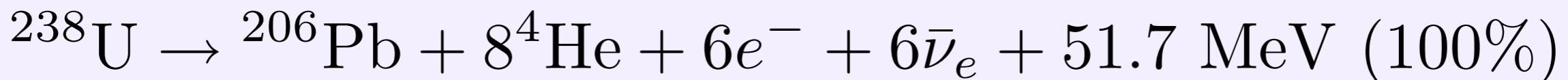
The 13th International Conference on Topics
in Astroparticle and Underground Physics

Sep. 9, 2013

Itaru Shimizu (Tohoku Univ.)

Geologically Produced Anti-Neutrino

Beta-decay of radioactivities (U, Th, K) in the Earth



Surface heat flow
44 TW

Bulk Silicate Earth (BSE) model

chondrite meteorite

U : 8 TW

Th : 8 TW

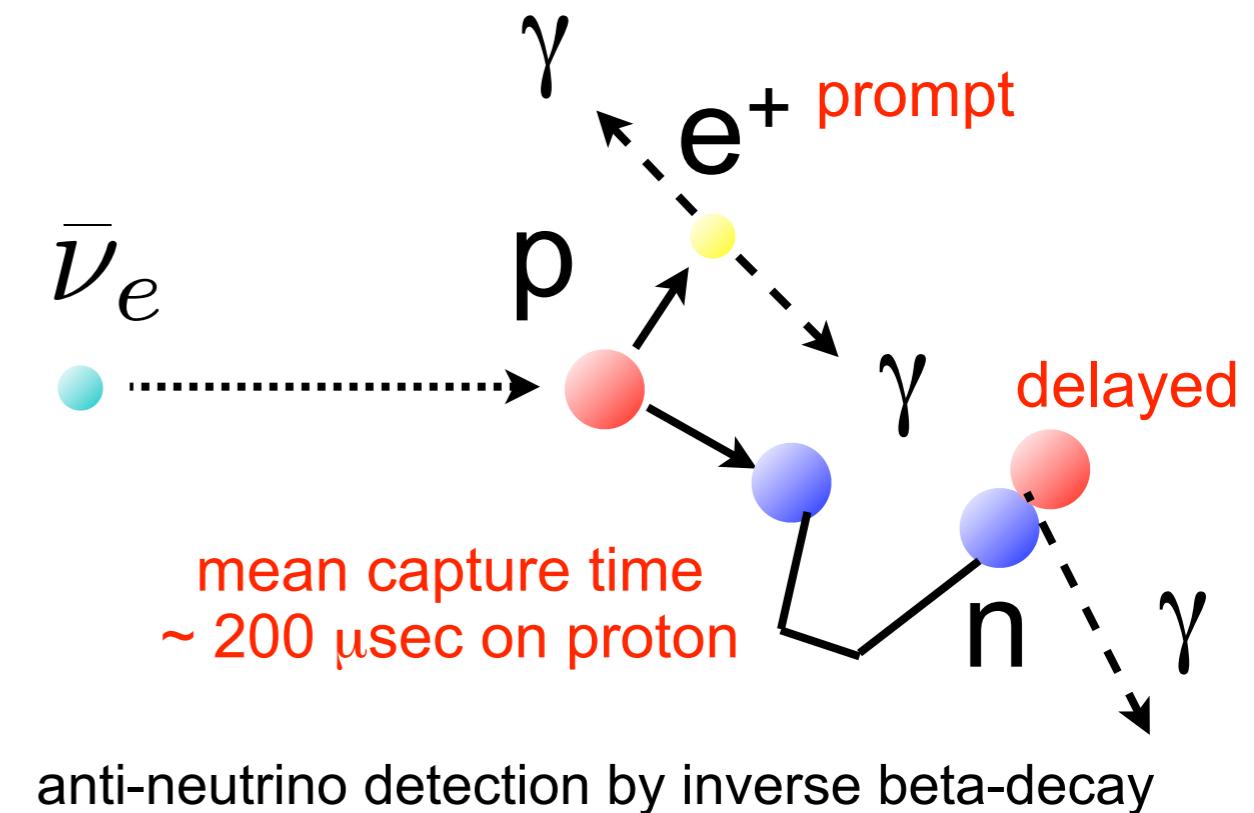
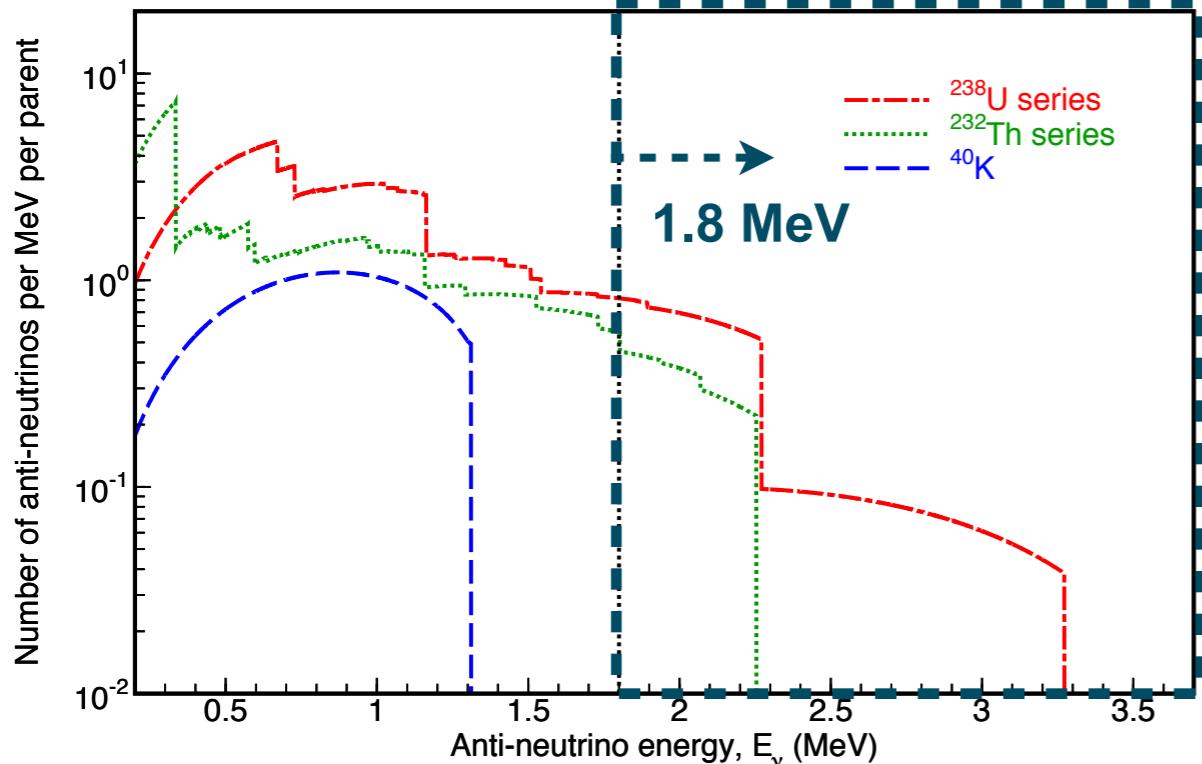
K : 4 TW



Radiogenic heat
19 TW

Geo Neutrino

- G. Eder (1966)
 - G. Marx (1969)
 - L. Krauss et al. (1988)
 - M. Kobayashi, Y. Fukao (1981)
 - R. Raghavan et al. (1998)
 - Rothschild et al. (1998)
 - G. Fiorentini et al. (2003)
- } first calculation in science literature
systematic search of target detector material
feasible plan in KamLAND and Borexino
detailed neutrino flux calculations



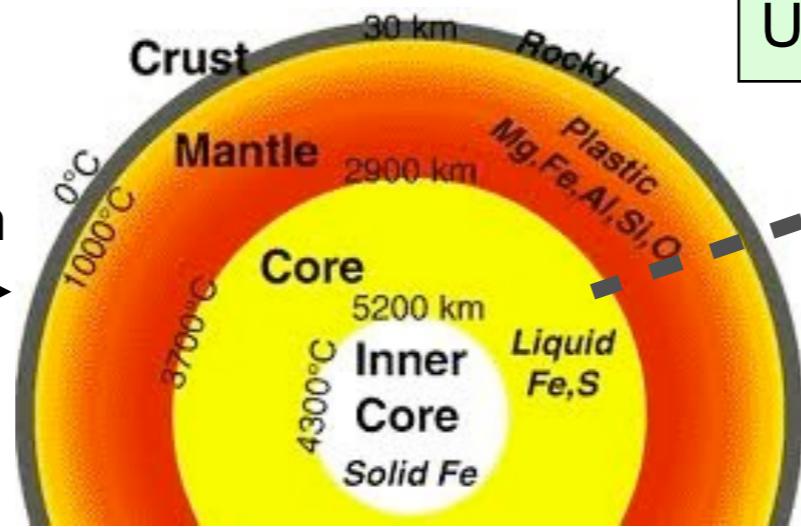
Neutrino Geoscience

Heat sources in the Earth

~ 4 billion years ago



Earth formation
→



Energy release by radioactive decay of U, Th, K → **radiogenic heat**

Release of gravitational energy through metallic core separation
→ **primordial heat**

still remain ?

5 Big Questions:

- What are earth's K/U & Th/U ratios?

planetary volatility curve

- Radiogenic contribution to heat flow?

secular cooling

- Distribution of reservoirs in mantle?

whole vs layered convection

- Radiogenic elements in the core??

Earth energy budget

- Nature of the Core-Mantle Boundary?

hidden reservoirs

Experimentally investigated

Geo neutrino detector

- KamLAND (Japan)

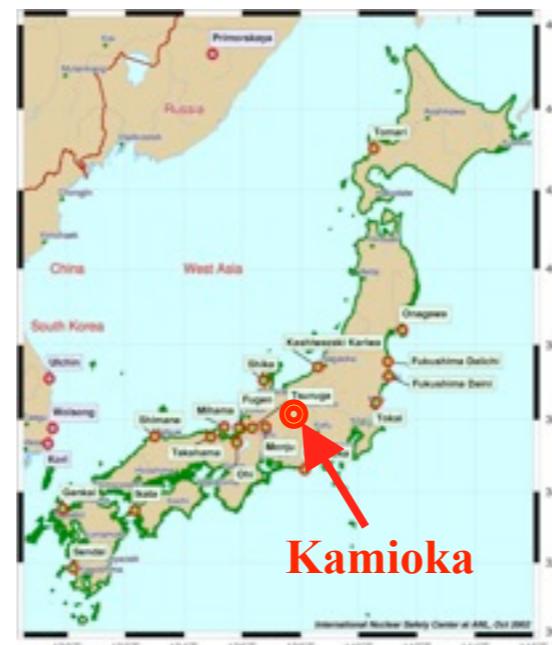
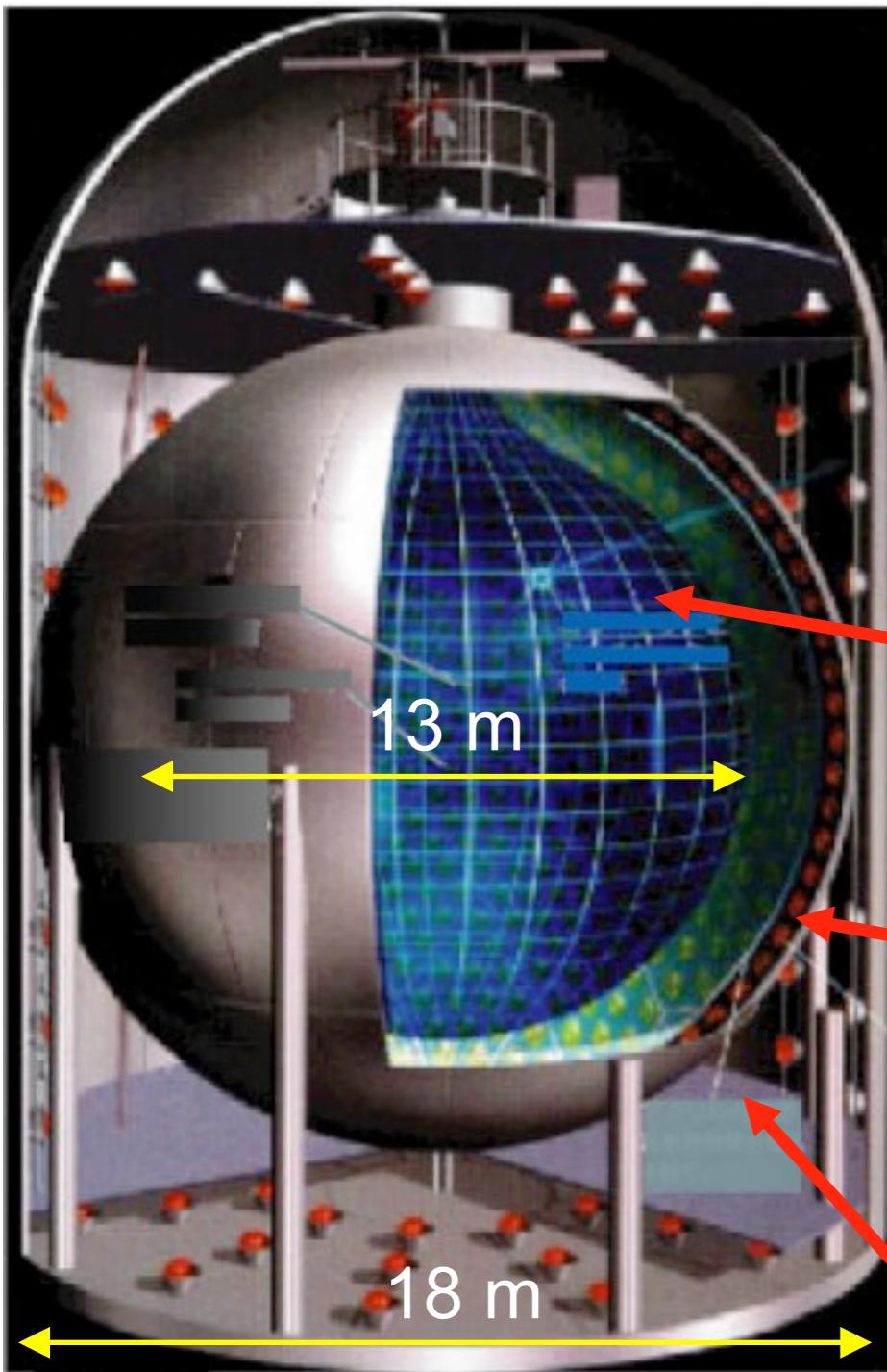
- Borexino (Italy)

Geo neutrino experiment will play a key role in answer all the questions !

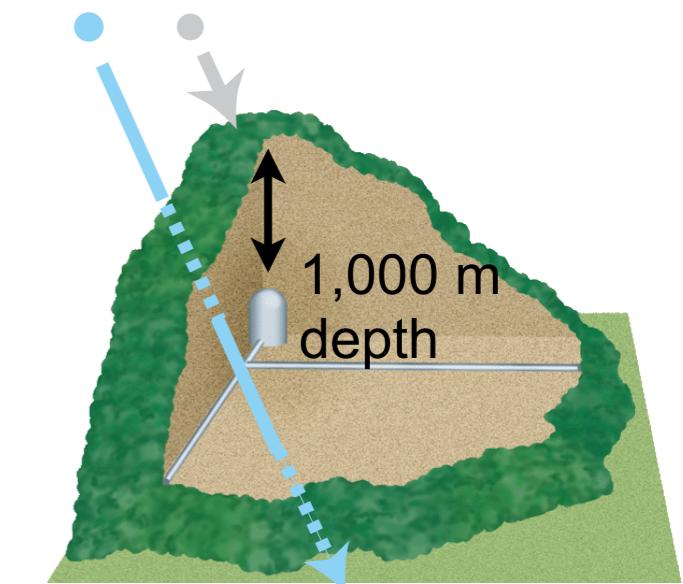
KamLAND

Kamioka Liquid Scintillator Anti-Neutrino Detector

operated since 2002



neutrino, cosmic-ray



1,000 ton Liquid Scintillator

Dodecane (80%) Pseudocumene (20%) PPO (1.36 g/l)

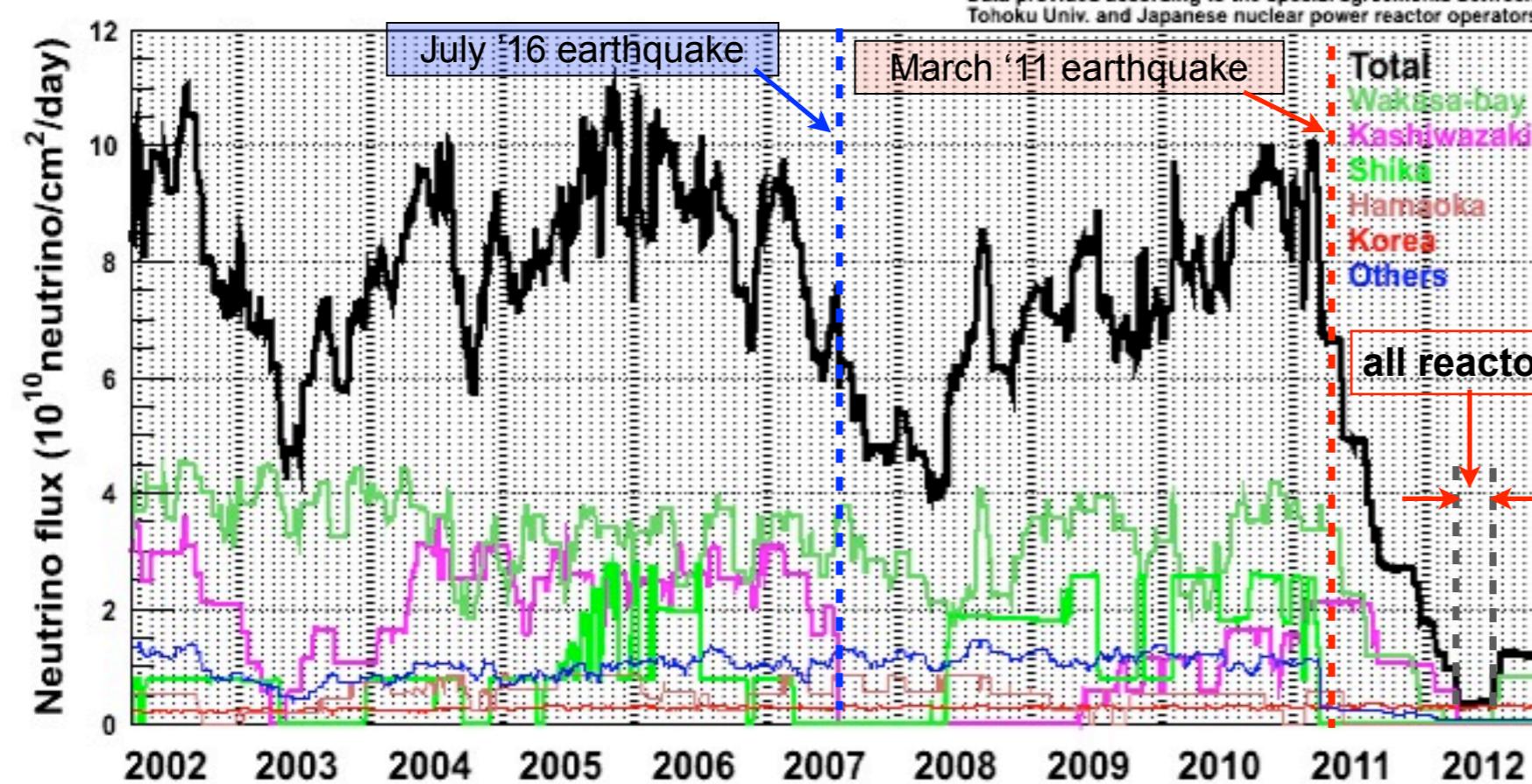
1,325 17 inch + 554 20 inch PMTs

commissioned in February, 2003
photocathode coverage : 22% → 34%

Water Cherenkov Outer Detector

Anti-Neutrino Flux in Kamioka

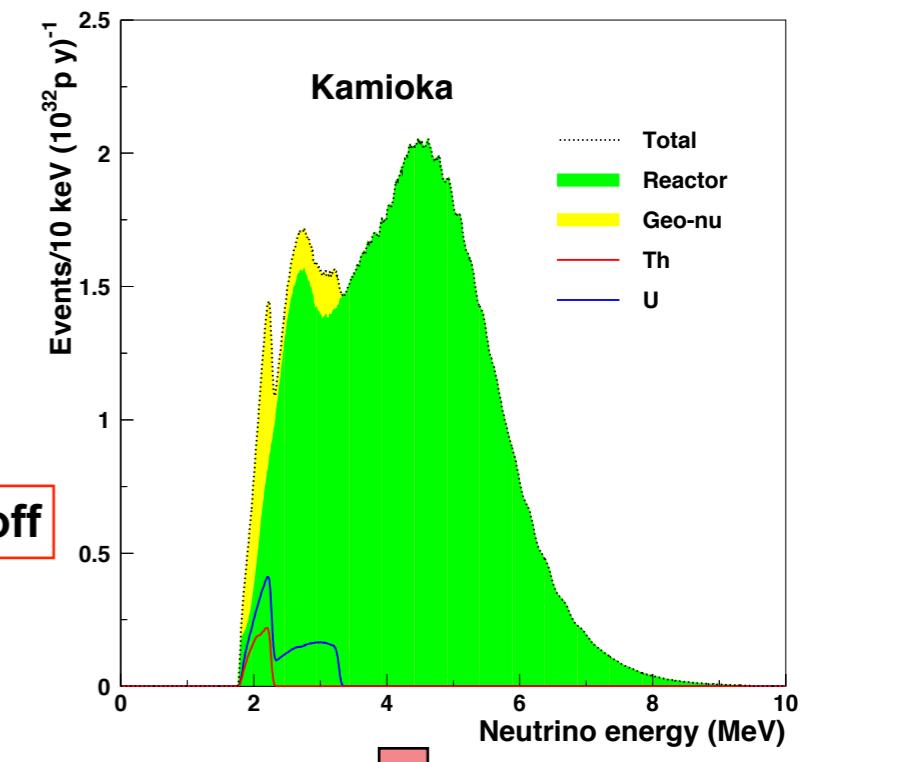
time variation of neutrino flux



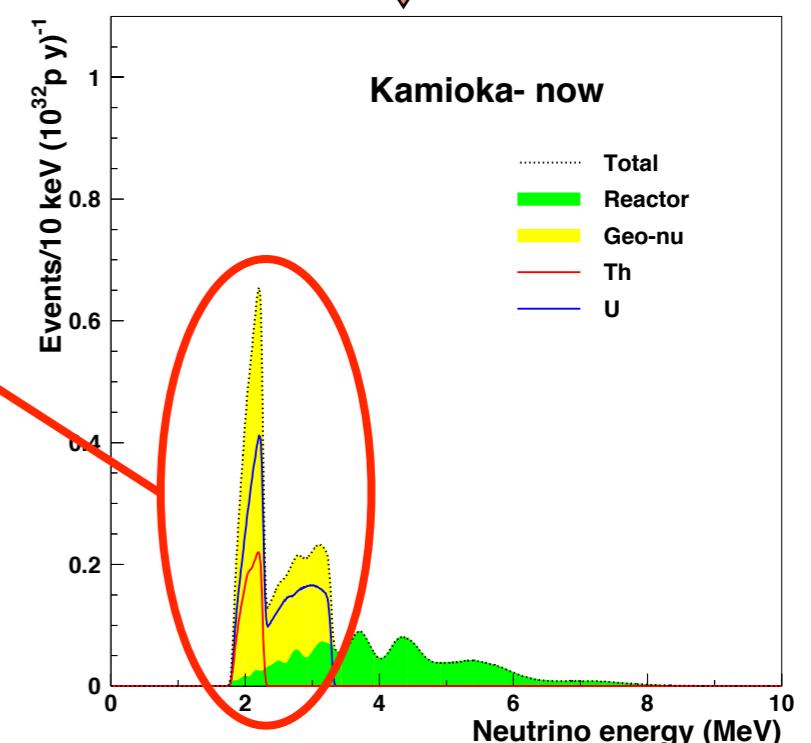
significant reduction of anti-neutrino flux from reactors after Fukushima-I accident

"Reactor on-off" study for neutrino oscillation and geo neutrino analysis

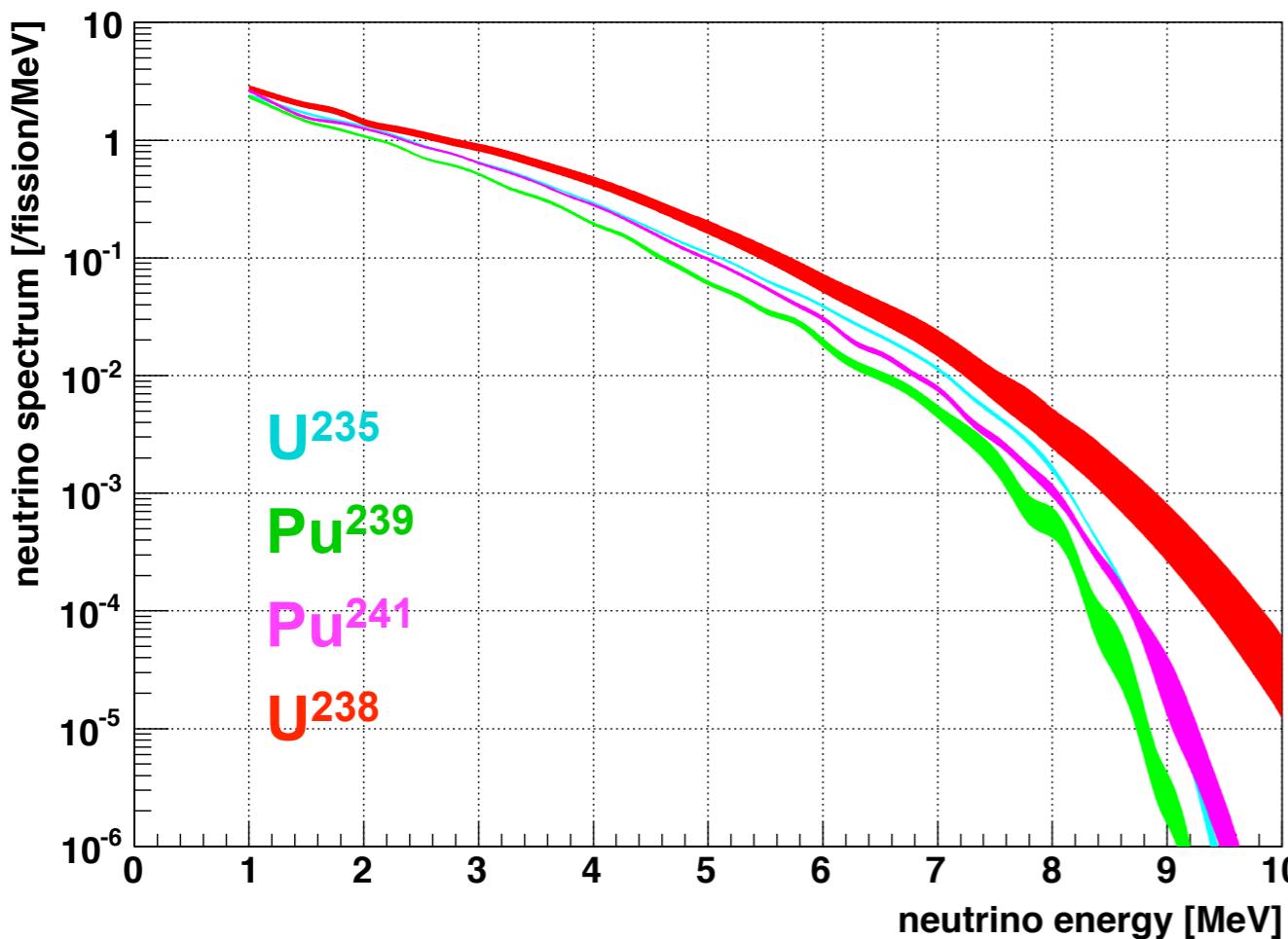
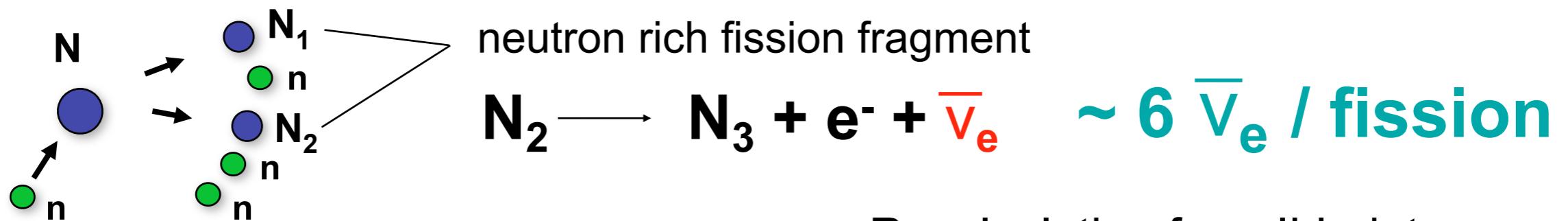
good data for geo neutrino observation



decrease of reactor neutrino



Reactor Neutrino Spectrum

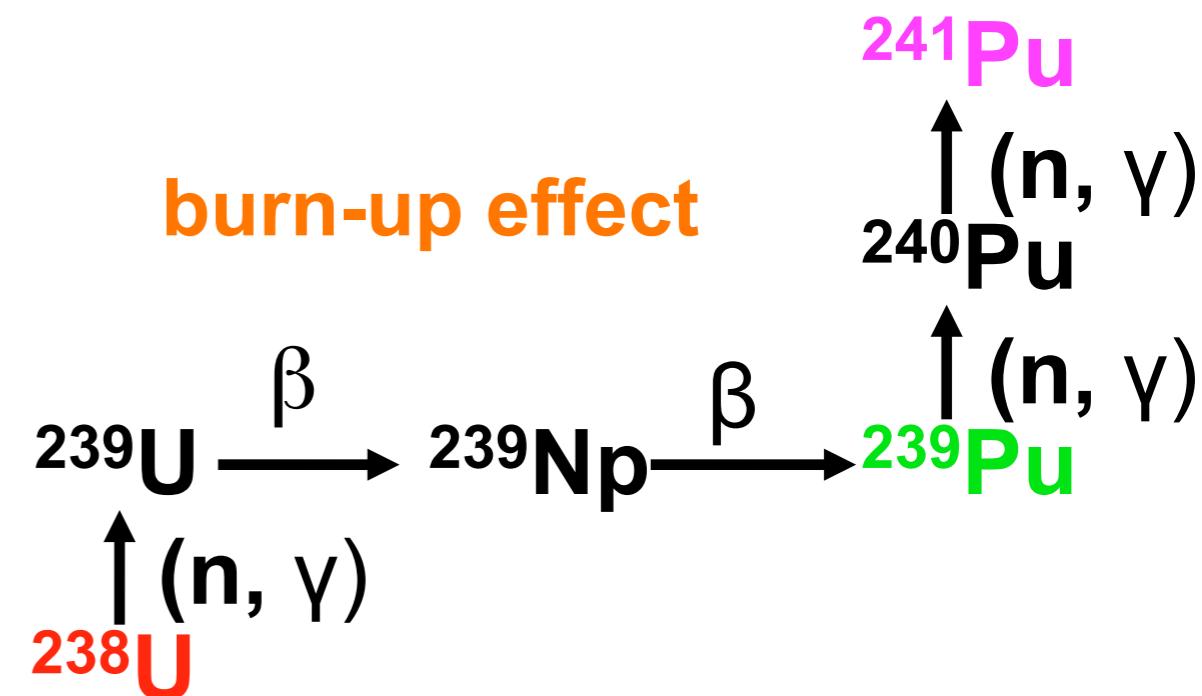


^{235}U , ^{239}Pu , ^{241}Pu : re-evaluation of ILL (P. Huber)

^{238}U : theoretical calculation (Th. Mueller et al.)

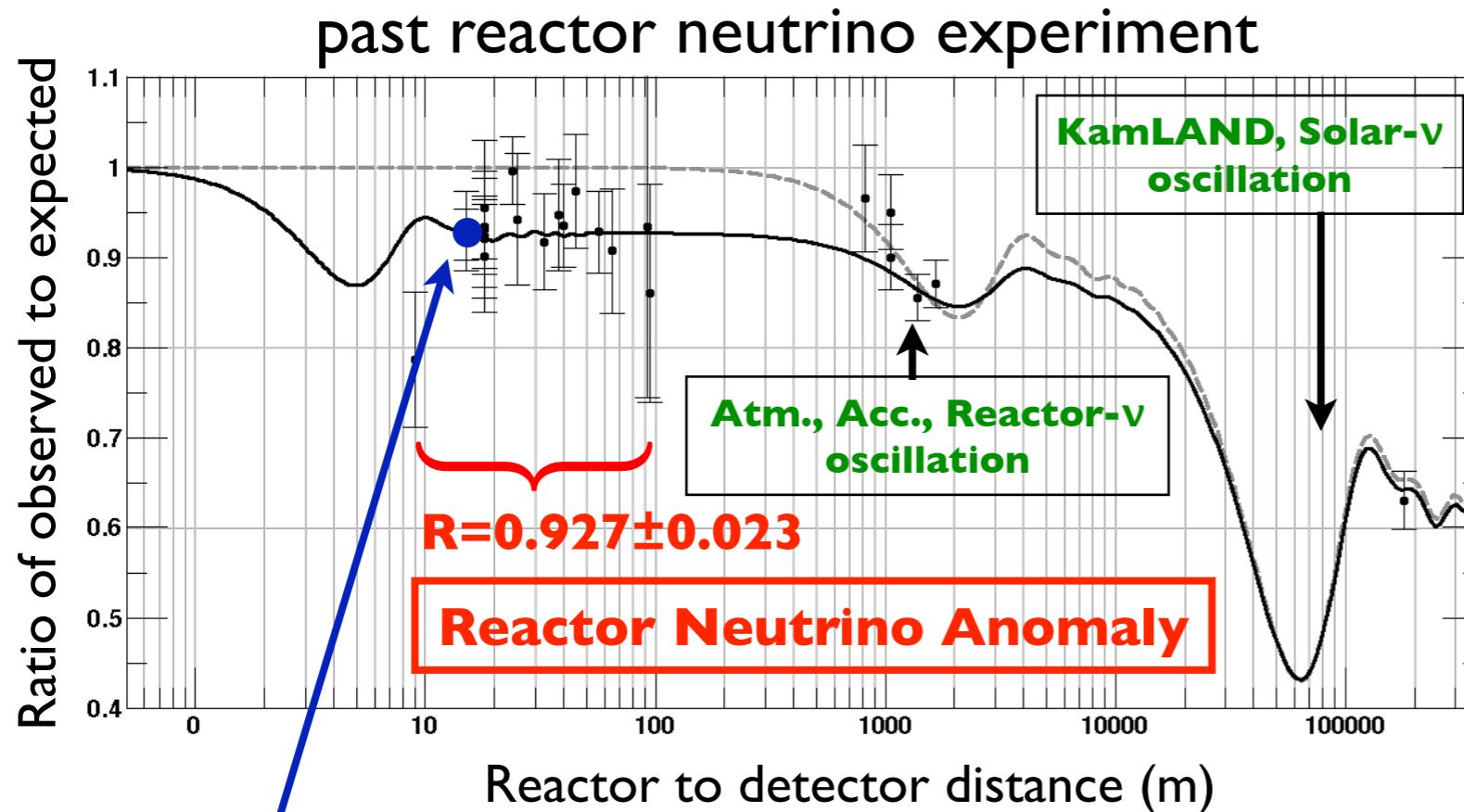
Recalculation from ILL data
(Lhuillier/Mueller, Saclay)

- built from 845 nuclei and 10000 β -branches
- introduce a new ab-initio conversion method
- includes full error propagation and correlation



~3% upward-shift by re-evaluation of ILL data

Normalization with Near Data



possibility of systematic bias
or sterile- ν oscillation?

Bugey4 accuracy on the neutrino flux is 1.4% ($L = 15$ m from PWR reactor)

Normalization of cross section per fission

$$\langle \sigma \rangle_{reac.} = \langle \sigma \rangle_{Bugey4} + \sum_i (\alpha_i^{reac.} - \alpha_i^{Bugey4}) \langle \sigma \rangle_i \quad (i = {}^{235}\text{U}, {}^{238}\text{U}, {}^{239}\text{Pu}, {}^{241}\text{Pu})$$

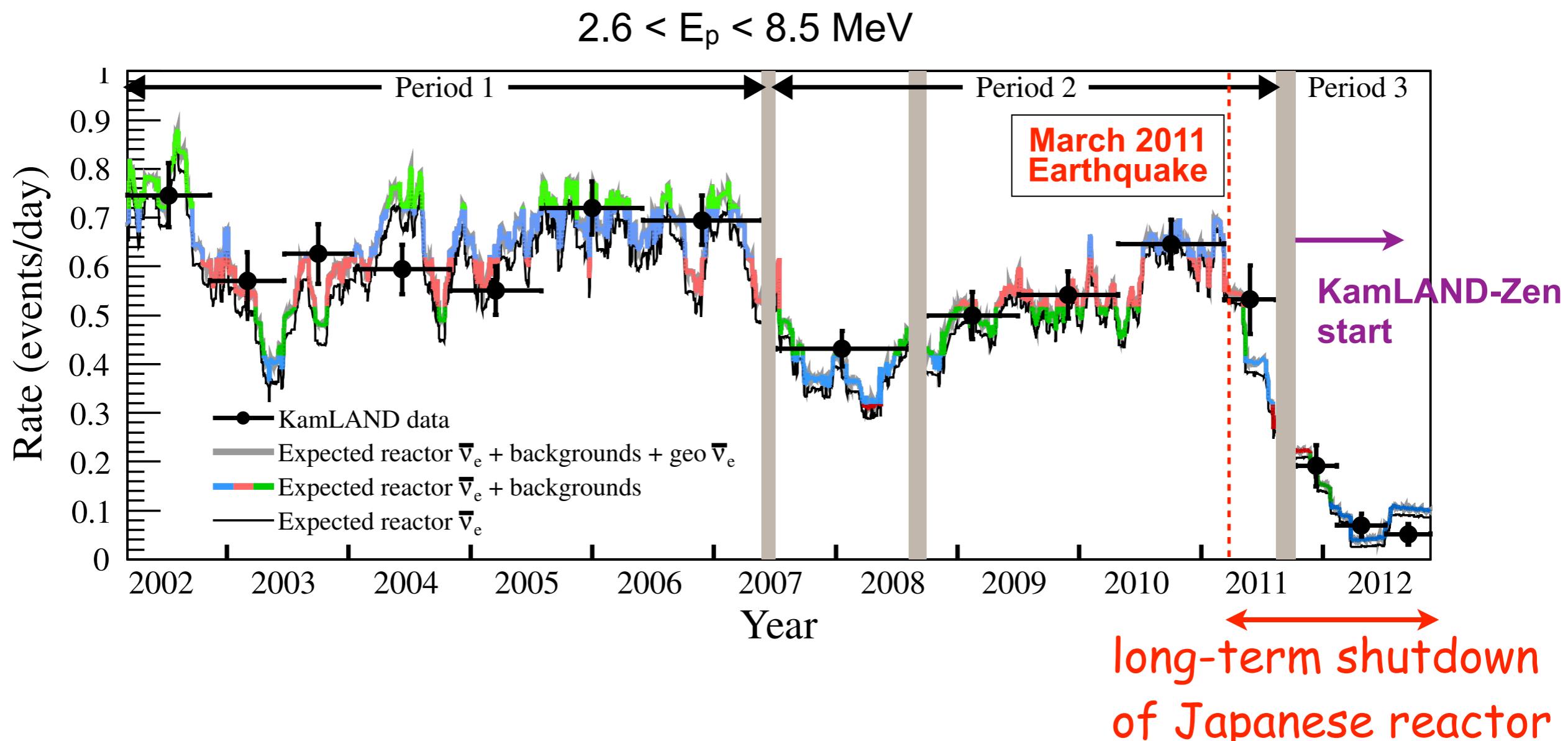
α_i : fractional fission rate $\langle \sigma \rangle_i = \int dE S_i(E) \sigma(E)$: effective cross section per fission

analysis is insensitive to "Reactor Neutrino Anomaly"

Time Variation of Event Rate

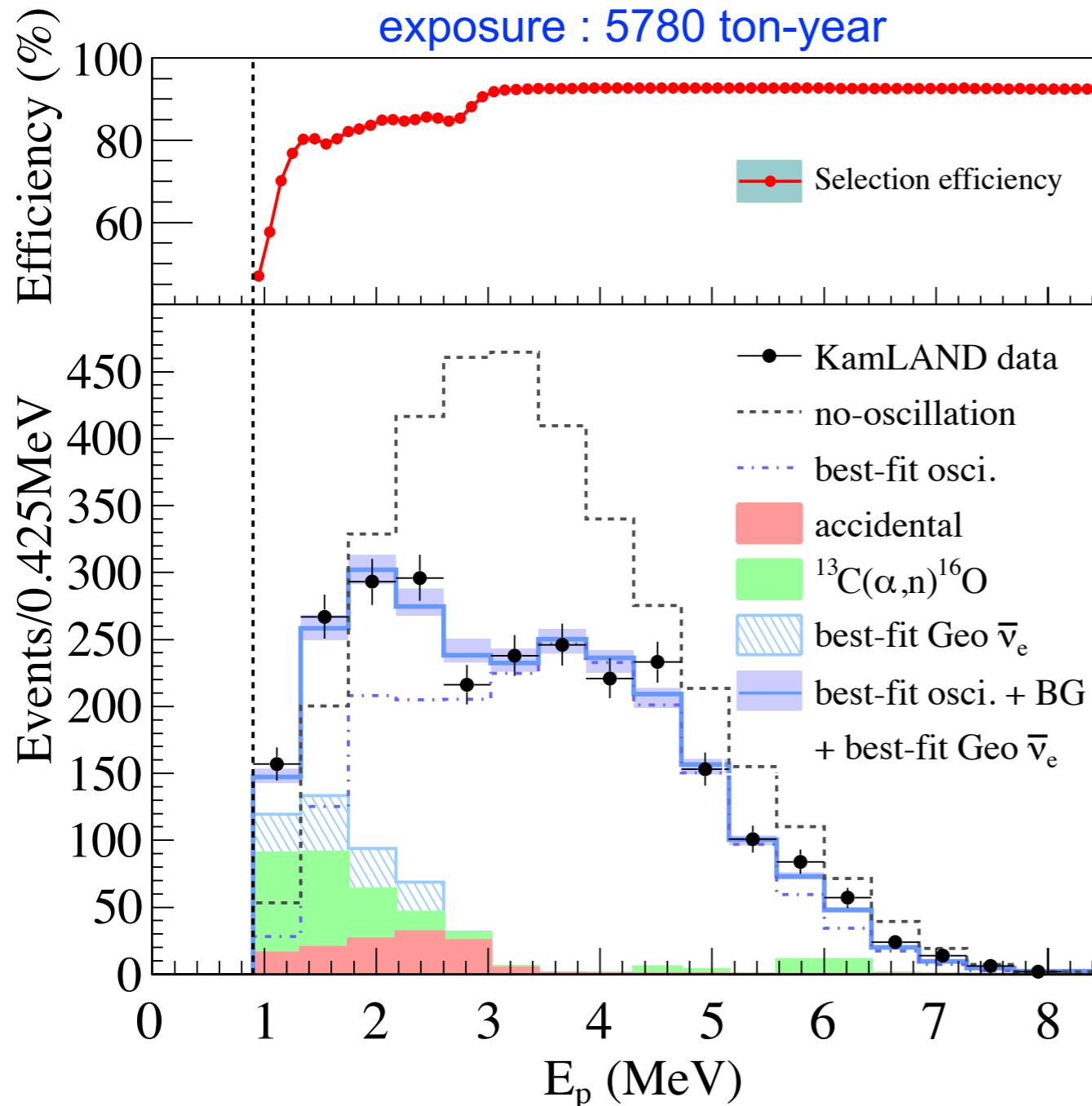
Total livetime
2991 days

Period 1: Mar. 2002 - May 2007
Period 2: May 2007 - Aug. 2011 (after LS purification)
Period 3: Oct. 2011 - Nov. 2012 (after KamLAND-Zen start)



Data have good agreement with expected rate

Observed Energy Spectrum



KamLAND only

$$\Delta m_{21}^2 = 7.54^{+0.19}_{-0.18} \times 10^{-5} \text{ eV}^2$$

$$\tan^2 \theta_{12} = 0.481^{+0.092}_{-0.080}$$

$$\sin^2 \theta_{13} = 0.010^{+0.033}_{-0.034}$$

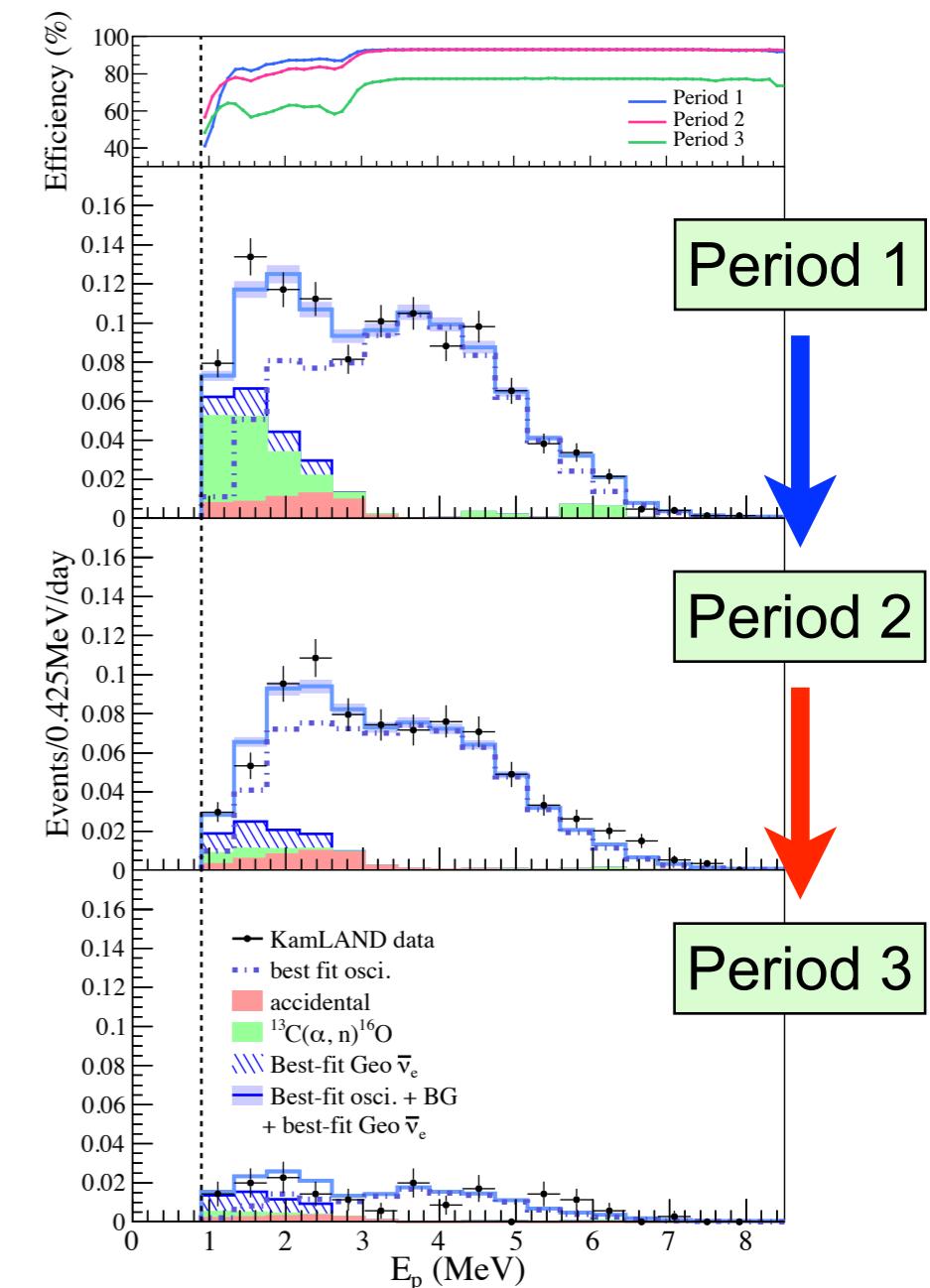
No osci. expected 3564 ± 145

Background
(w/o geo neutrino)

Observed events

364 ± 31
 2611

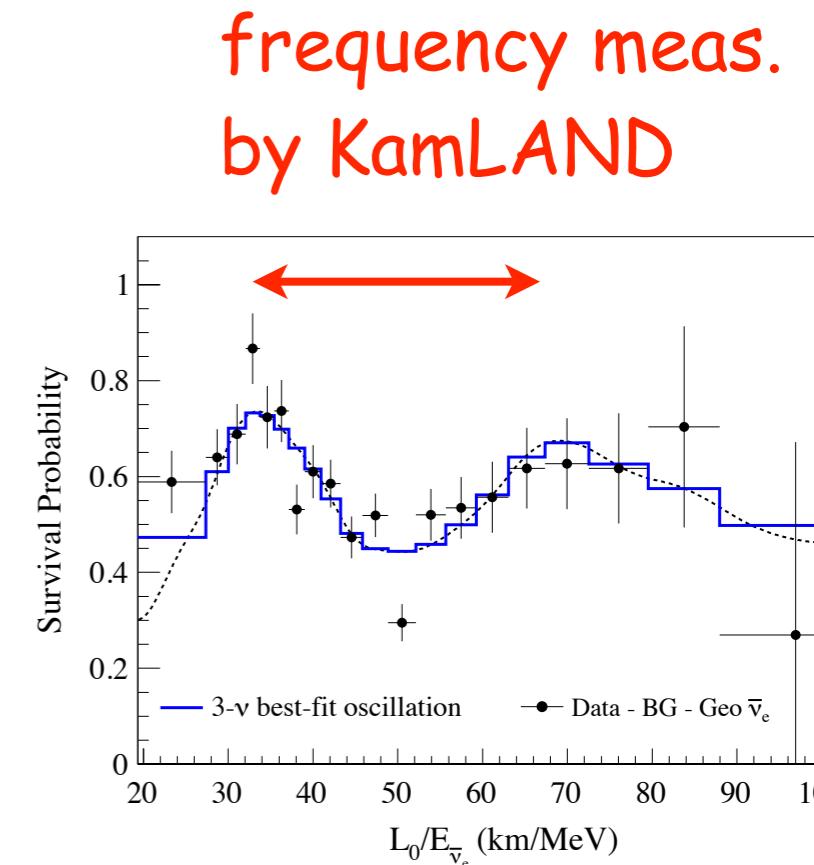
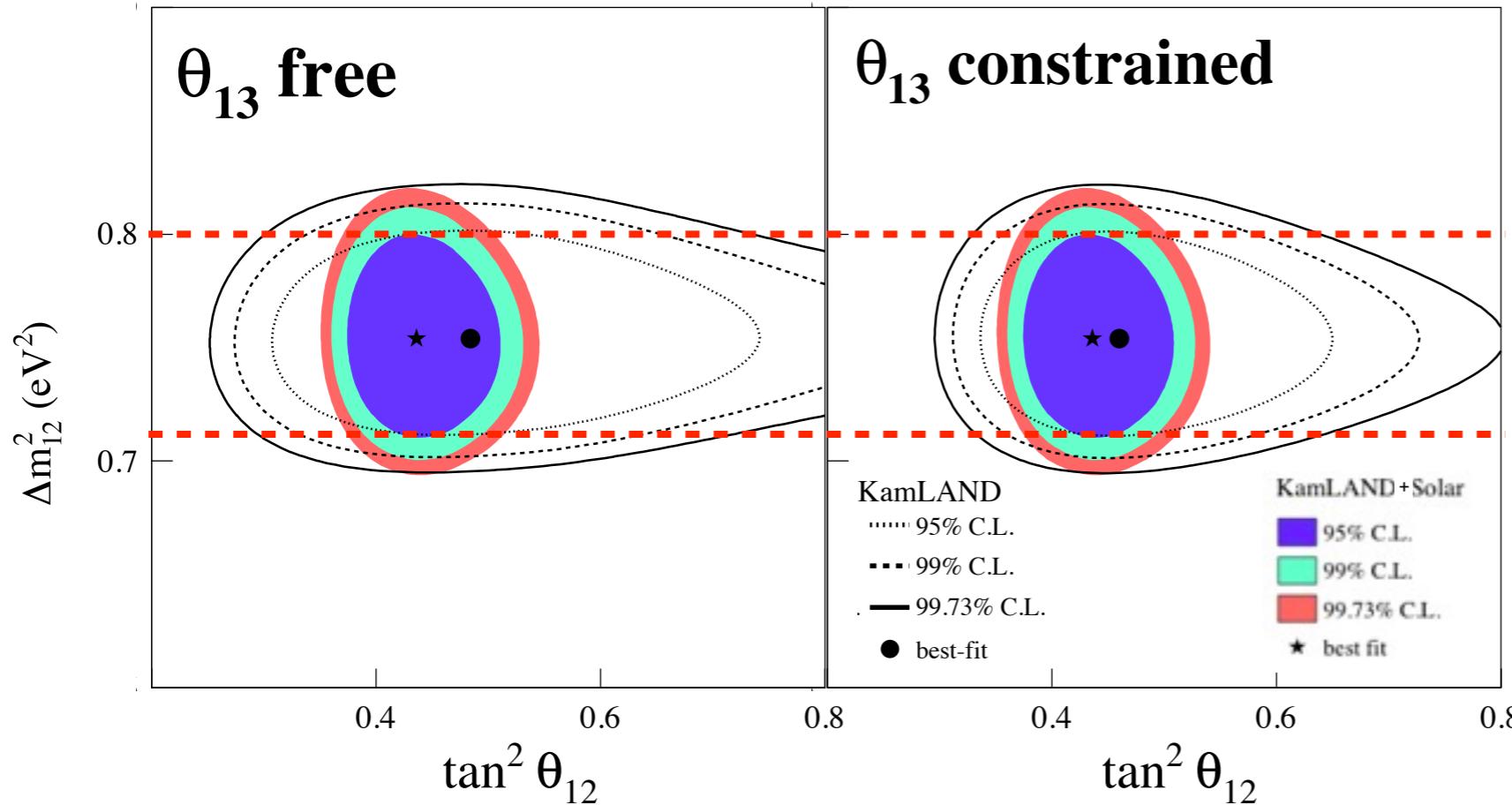
purification
earthquake
(α, n) ↓
reactor ↓



significant reduction

Neutrino Oscillation Parameter

Δm^2 : systematic uncertainty 1.9%
 (dominated by linear energy scale uncertainty)



KamLAND+Solar

$$\Delta m_{21}^2 = 7.53^{+0.19}_{-0.18} \times 10^{-5} \text{ eV}^2$$

$$\tan^2 \theta_{12} = 0.437^{+0.029}_{-0.026}$$

$$\sin^2 \theta_{13} = 0.023^{+0.015}_{-0.015}$$

KamLAND+Solar+ θ_{13}

$$\Delta m_{21}^2 = 7.53^{+0.18}_{-0.18} \times 10^{-5} \text{ eV}^2$$

$$\tan^2 \theta_{12} = 0.436^{+0.029}_{-0.025}$$

$$\sin^2 \theta_{13} = 0.023^{+0.002}_{-0.002}$$

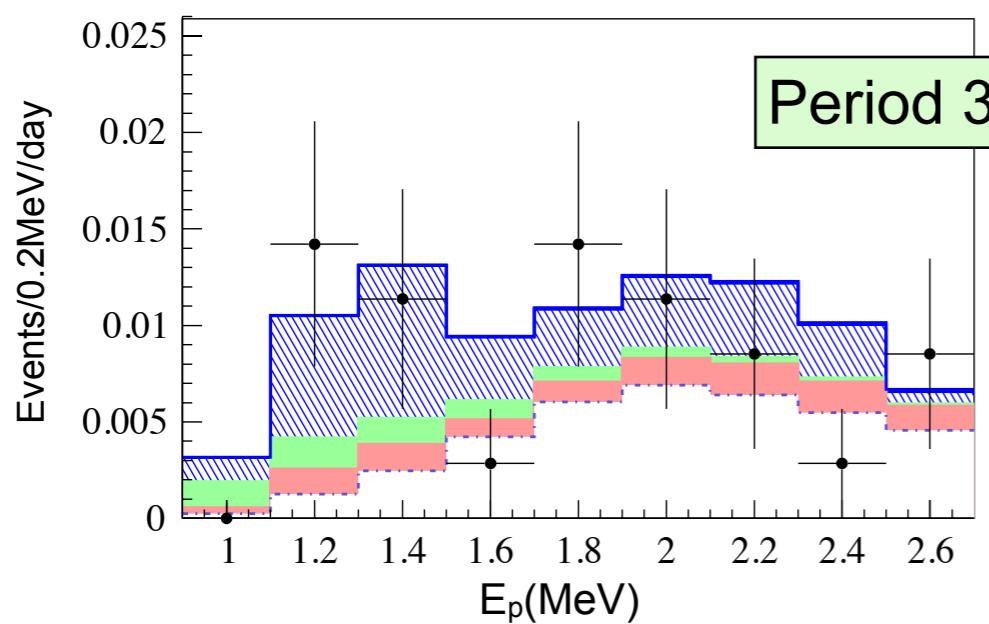
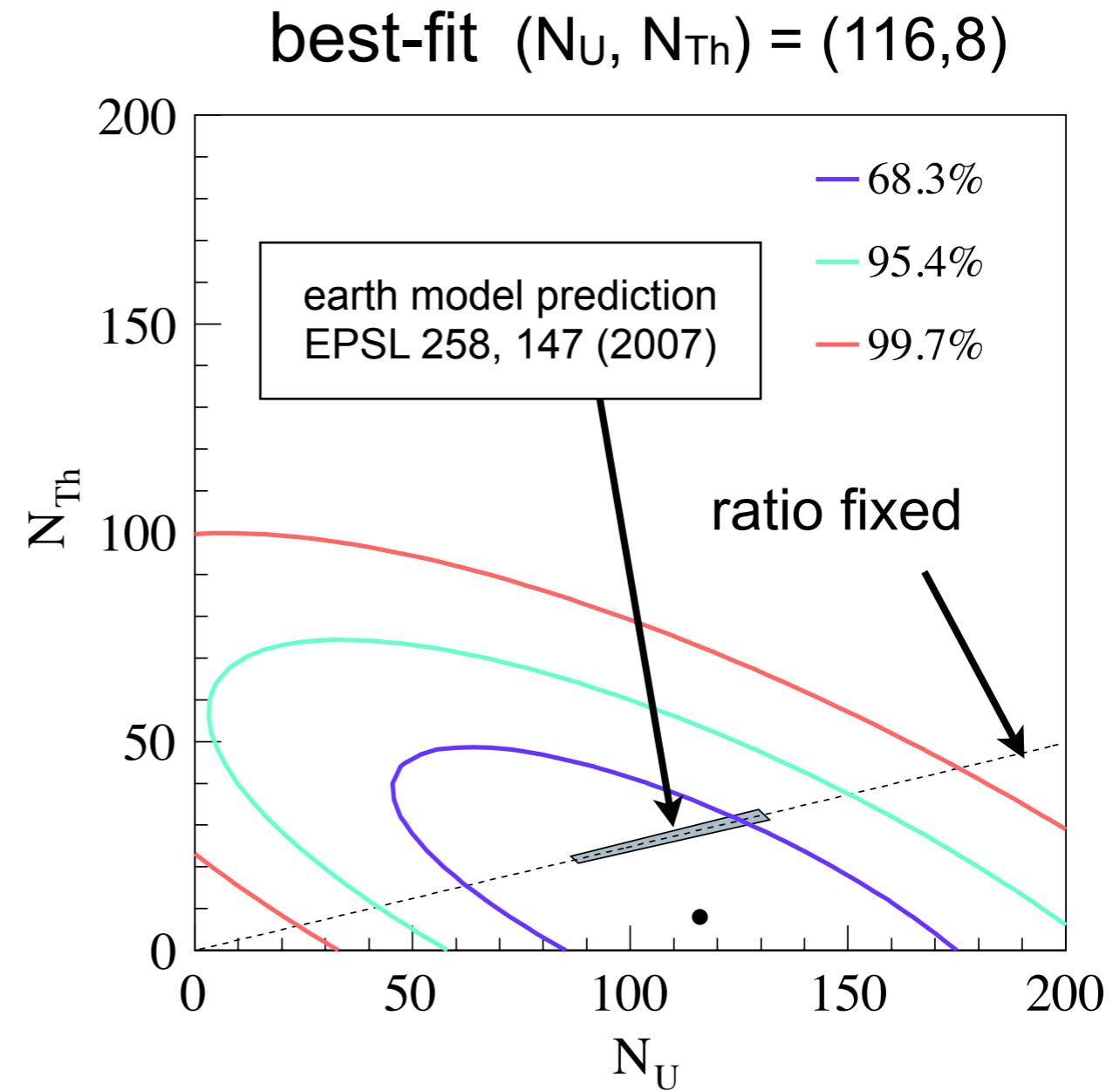
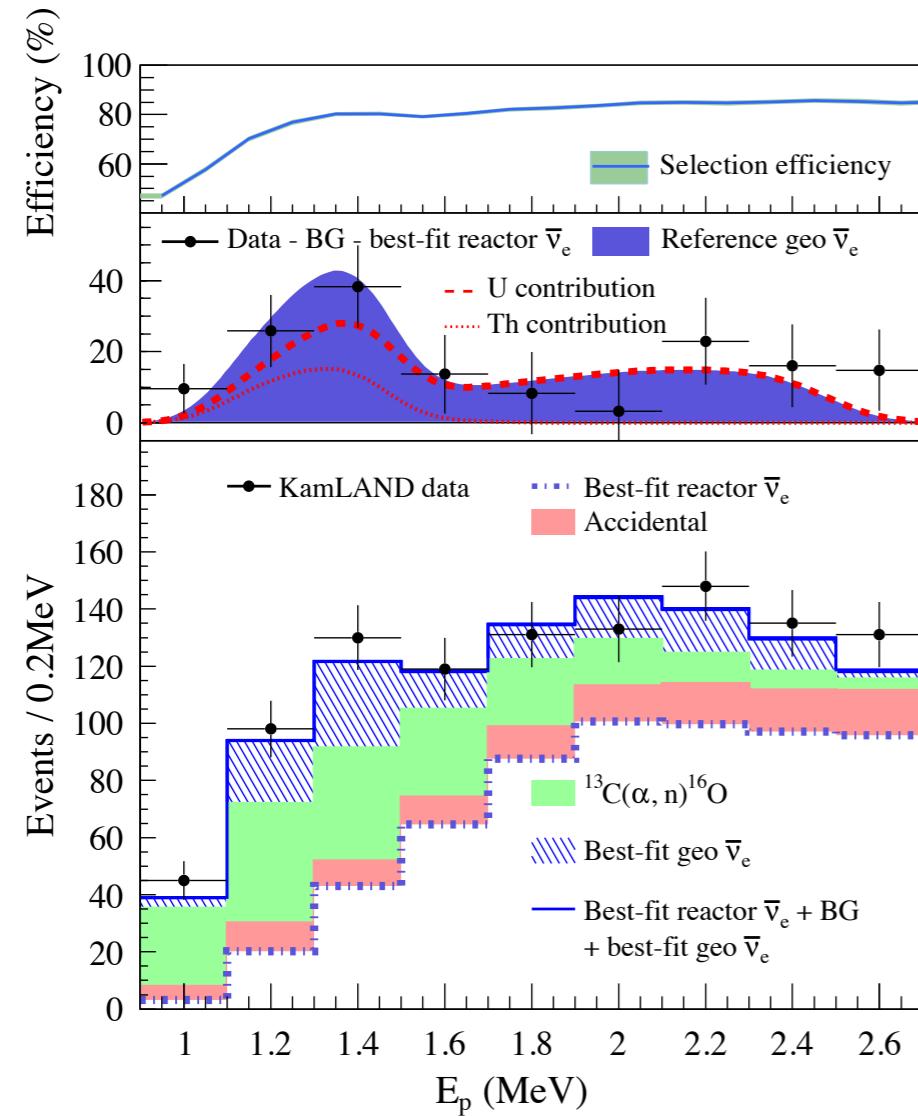
θ_{13} constraint

← insensitive

← no strong impact

Survival probability of geo $\bar{\nu}_e = 0.511 \pm 0.014$ (2.7%)

Fit with U/Th components



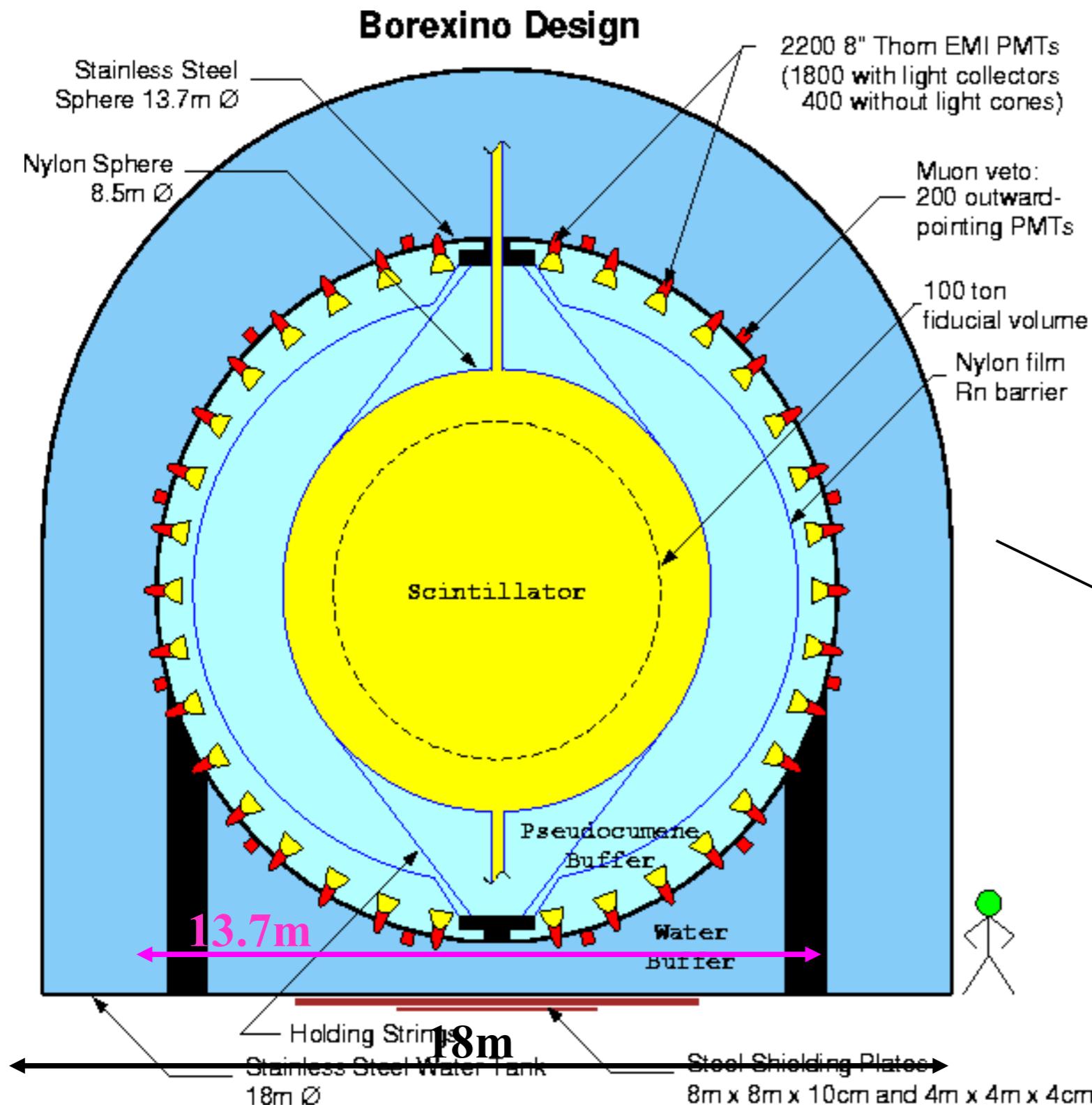
$N_{\text{geo}} = 116^{+28}_{-27}$ events

$F_{\text{geo}} = 3.4^{+0.8}_{-0.8} \times 10^6 / \text{cm}^2/\text{sec}$

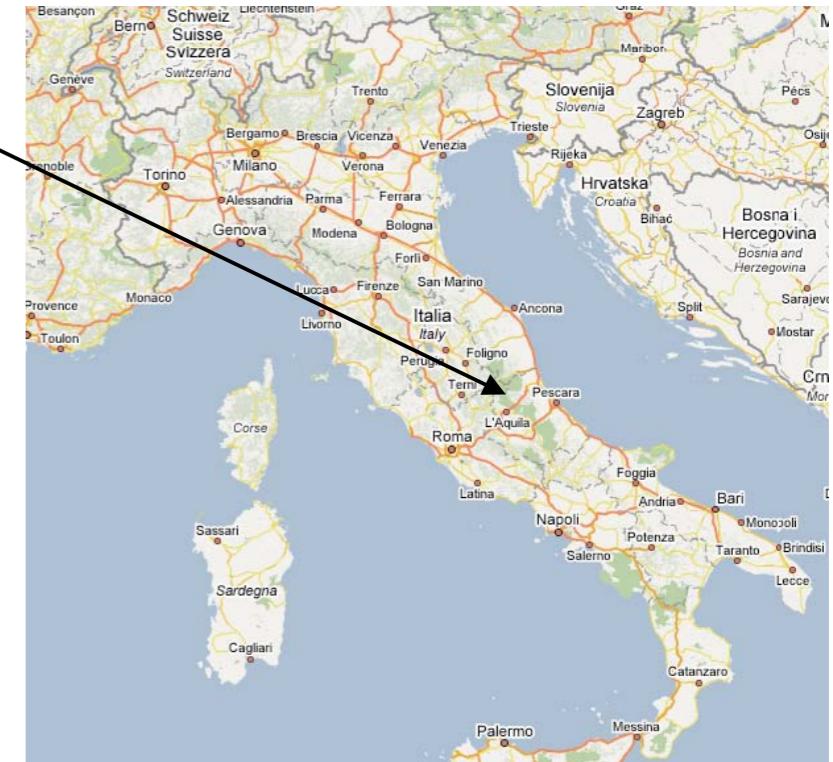
$(30.7^{+7.5}_{-7.3} \text{ TNU})$

Borexino

Smirnov, TAUP 2011

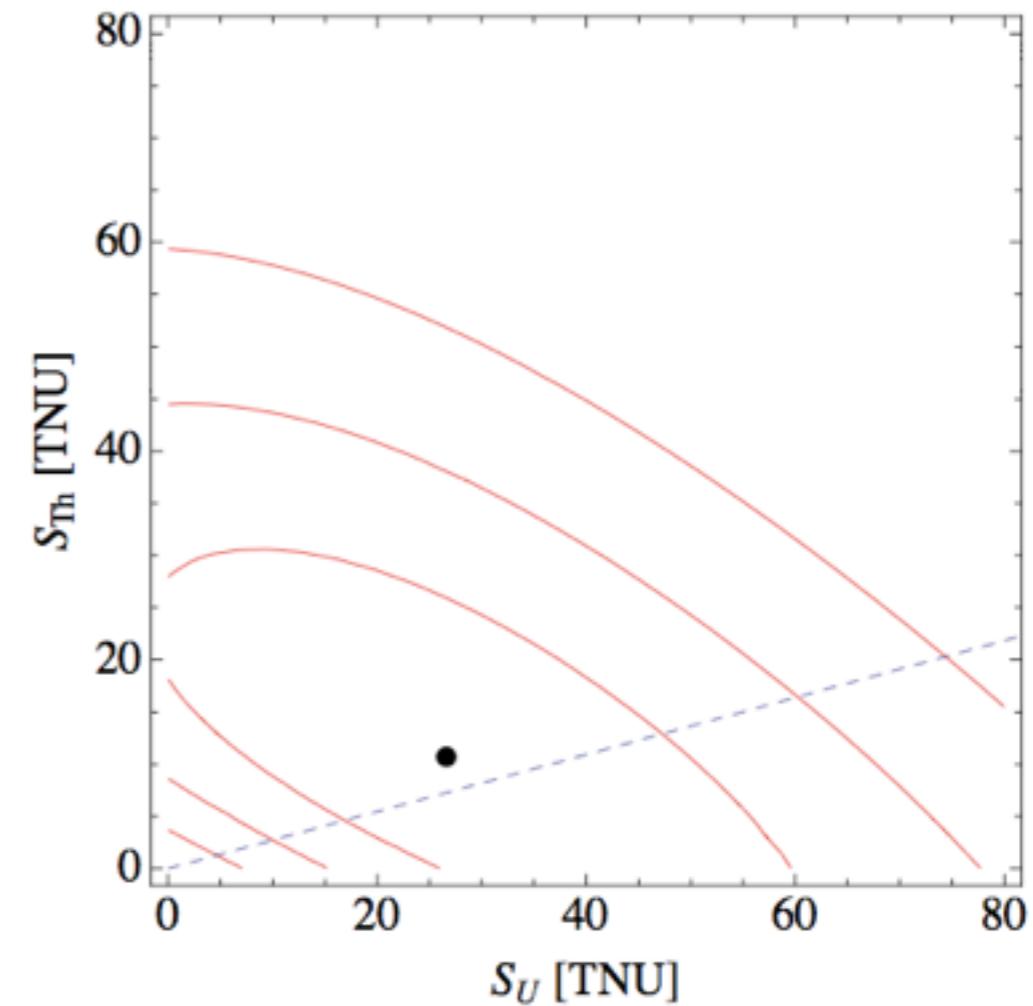
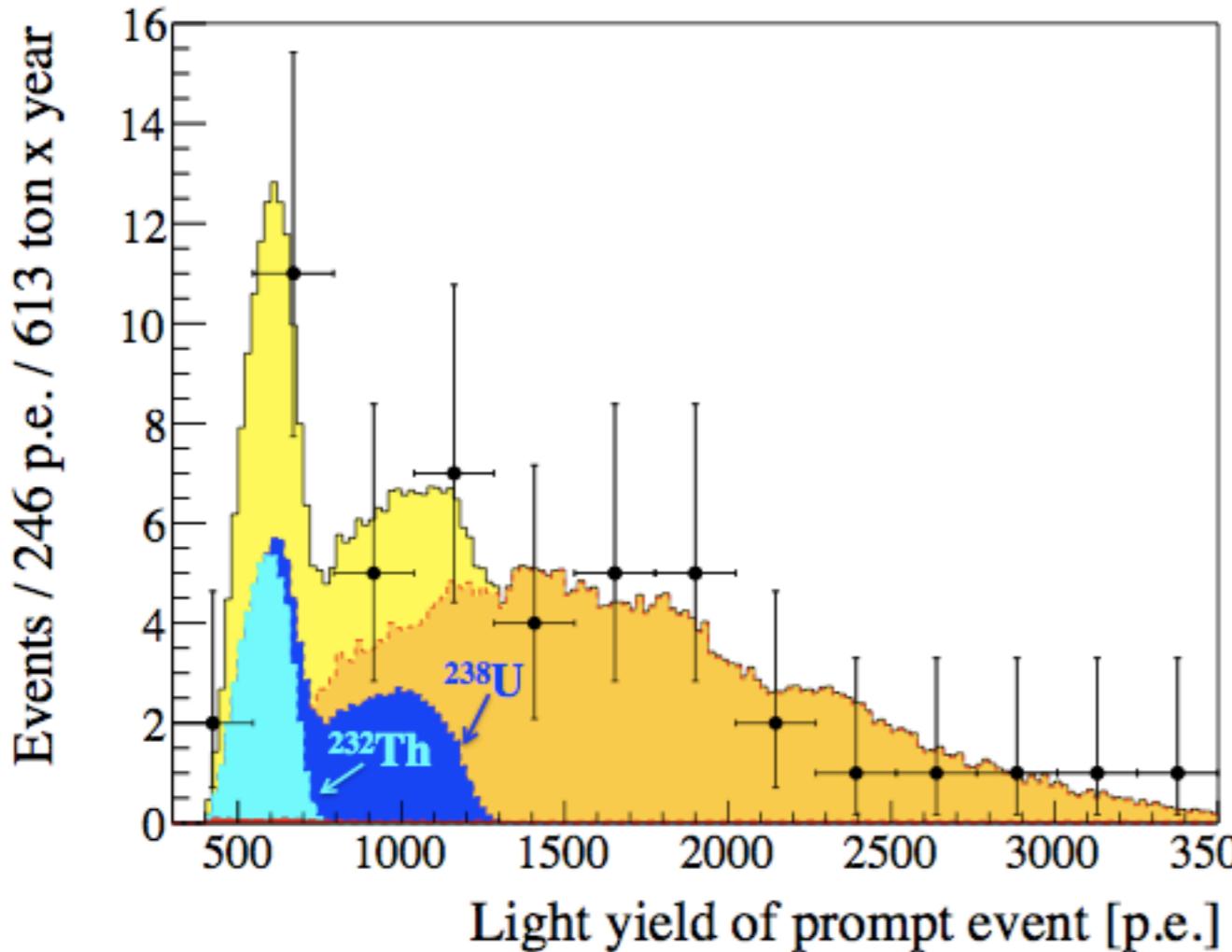


- 278 t of liquid organic scintillator PC + PPO (1.5 g/l)
 - (ν, e)-scattering with 200 keV threshold
 - Outer muon detector



Fit with U/Th components

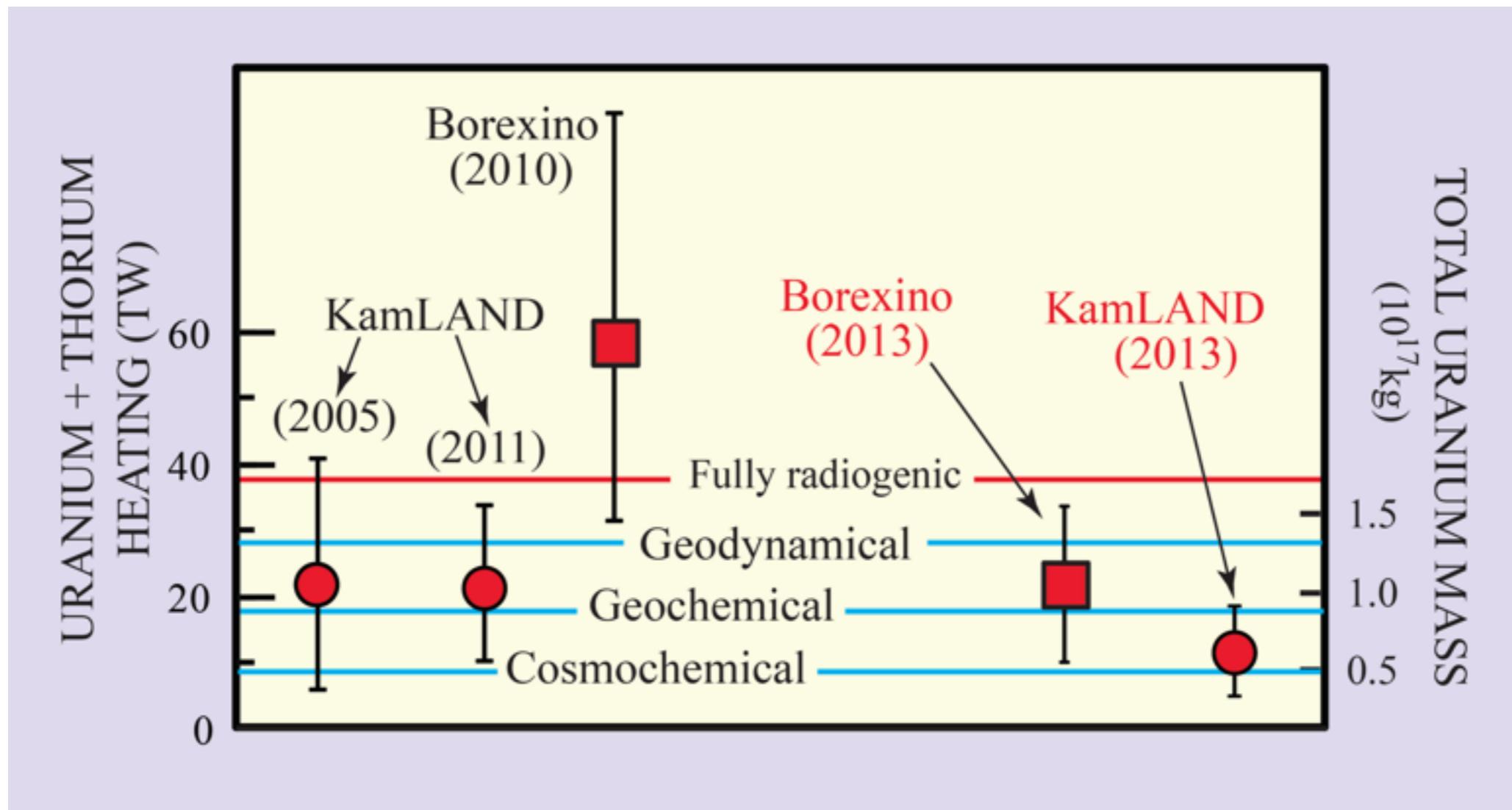
Zavatarelli, Neutrino Geoscience 2013



N_{reactor} Expected with osc.	N_{reactor} Expected no osc.	Others back.	N_{geo} measured	N_{reactor} measured	N_{geo} measured	N_{reactor} measured
events	events	events	events	events	TNU	TNU
33.3 ± 2.4	60.4 ± 4.1	0.70 ± 0.18	14.3 ± 4.4	$31.2_{-6.1}^{+7}$	38.8 ± 12.0	$84.5_{-16.9}^{+19.3}$

Summary of Geo Neutrino Results

McDonough, Neutrino Geoscience 2013



MODELS'

- Cosmochemical:'uses'meteorites'–'O'Neill'&'Palme'('08);'Javoy'et'al'('10);'Warren'('11)'
- Geochemical:'uses'terrestrial'rocks'–'McD'&'Sun'95;'Allegre'et'al'95;'Palme'&'O'Neil'03'
- Geodynamical:'parameterized'convecBon'–'Schubert'et'al; 'TurcoHe'et'al; 'Anderson'

Agreement of results at multi-site

Earth Model Comparison

Three classes BSE compositional estimates

O. Šramek et al. Earth. Plan. Sci. Letters 361 (2013) 356–366

Model	Cosmochem.	Geochem.	Geodyn.
A_{U} (ppb)	12 ± 2	20 ± 4	35 ± 4
A_{Th} (ppb)	43 ± 4	80 ± 13	140 ± 14
A_{K} (ppm)	146 ± 29	280 ± 60	350 ± 35
Th/U	3.5	4.0	4.0
K/U	12000	14000	10000
Tot. Power (TW)	11 ± 2	20 ± 4	33 ± 3
Mantle power (TW)	3.3 ± 2.0	12 ± 4	25 ± 3
Mantle Urey ratio	0.08 ± 0.05	0.3 ± 0.1	0.7 ± 0.1

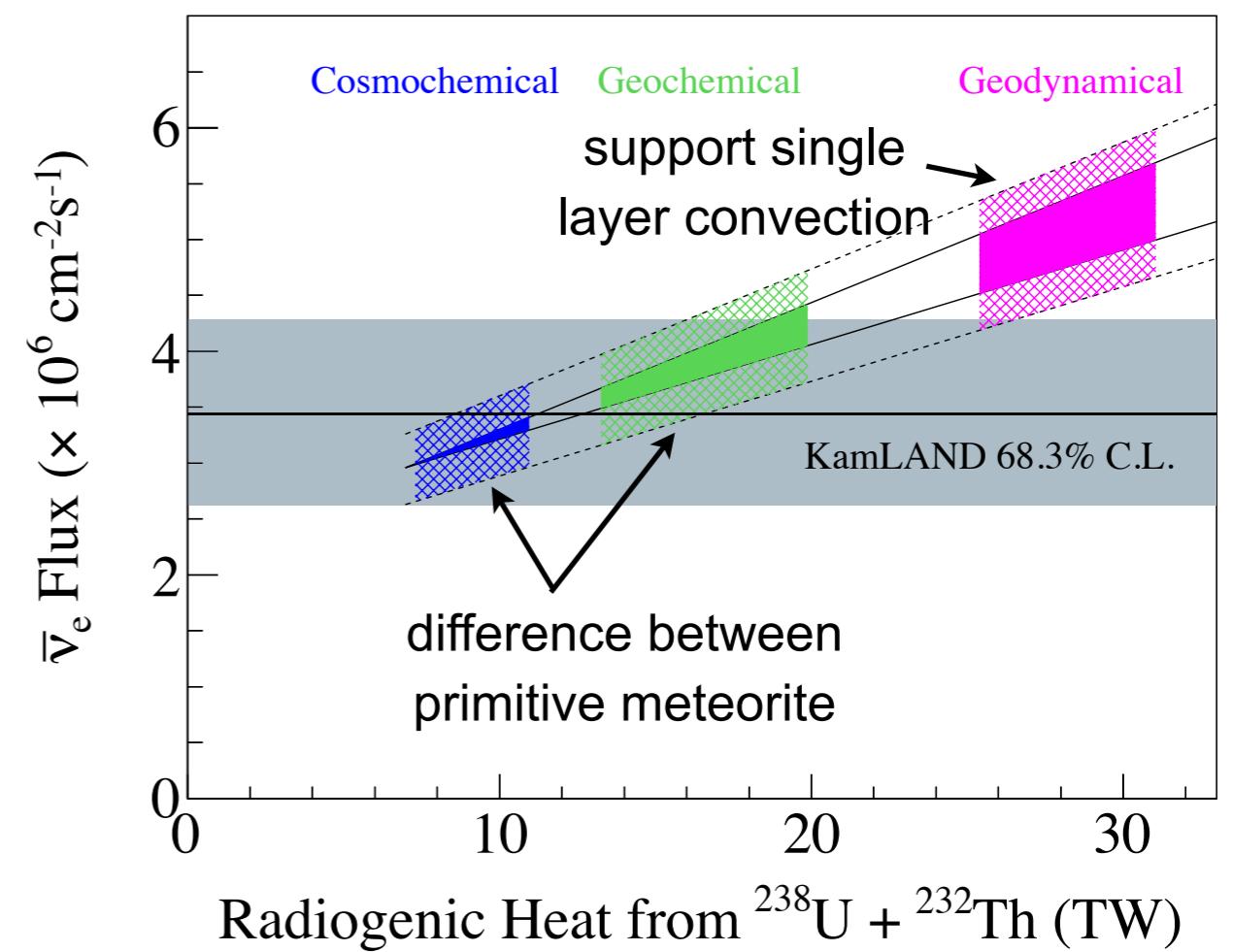
KamLAND result (2013)

radiogenic $14.2^{+7.9}_{-5.1}$ TW

heat low from
Earth's surface

47 ± 2 TW

Geo-v measurement is in agreement with BSE models



Geodynamical prediction with homogeneous hypothesis is disfavored at 89% C.L.

All composition models are still consistent within $\sim 2\sigma$

Physicist/Geoscientist Collaborative Work

Neutrino Geoscience 2013 International Workshop (Takayama in Japan)



<http://www.awa.tohoku.ac.jp/geoscience2013/>

“Neutrino Geoscience” is developing

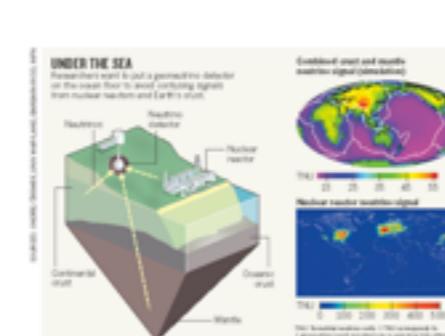
- Earth model from geophysics and geochemistry
- Multi-site measurement by neutrino detectors



detailed map of neutrino source inside the Earth

International scientific community is organized

Nature News in April 2013



Detectors zero in on Earth's heat

Geoneutrinos paint picture of deep-mantle processes.

BY ALICIA WITZE

A heat wave in the deep Earth opened unexpectedly in 2011, when Japan's nuclear reactors went into shutdown after the Fukushima disaster. Before the disaster, an underground particle detector called KamLAND, based in Kamioka, Japan, was monitoring a torrent of neutrinos streaming from dozens of nearby nuclear reactors, working close to the nuclei of these hard-to-catch subatomic particles. After those plants fell silent, KamLAND scientists could see more clearly a signal that had largely been obscured: a trickle of neutrinos produced inside the planet.

But no one knew the proportions. Geologists assume that Earth contains the same amount of radioactive elements as certain primitive meteorites, but they aren't sure. "We're after trying to understand how Earth was built," says William McDonnell, a geologist at the University of Maryland in College Park.

Enter KamLAND and Borexino, which spot geoneutrinos as a sideline to their other neutrino studies. Both experiments use liquid scintillator detectors, in which huge rats of fluid capture the occasional spark of light when a passing neutrino interacts with atomic nuclei in the liquid.

The team of Borexino, a vat containing 300 tonnes of liquid buried under the Italian Alps, captured 14 candidate geoneutrinos between December 2005 and August 2012 (see T. J. Stange et al. *Nature* 490, 49–52; 2012).

Scientists at KamLAND, with 1,000 tonnes of liquid, say that they detected 116 probable geoneutrinos between March

2002 and November 2012 (see C. S. Ratti et al.).

That's just enough for researchers to start drawing conclusions about the composition of Earth's mantle, says McDonnell. Assuming that uranium and thorium are spread uniformly in the mantle, the KamLAND findings suggest that about 11 of the 47 TN come from the radioactive decay of these elements. A similar calculation for Borexino yields about 18 TN.

Ultimately, geoneutrino researchers would like multiple detectors spaced around Earth, so that they could perform a sort of tomography on the mantle. That could help scientists to discern between models that theorize the uranium and thorium being spread throughout the mantle, versus ones in which the elements are concentrated near the core–mantle boundary. Such a difference could help to determine where and how long heat will continue to flow to drive geological processes such as plate tectonics — and how long it will take Earth to cool.

One challenge is that uranium and thorium much nearer the surface in the continental crust can mask the geoneutrino signal coming from deeper in the planet (see “Under the sea”). Next year, for example, the retooled Sudbury Neutrino Observatory (SNO) in Ontario, Canada, will start taking data with a 780-tonne detector that is sensitive to geoneutrinos. But SNO — as the upgrade is called, its mask in the middle of continental crust, impeding core flow — may have died, says Steve Bryn, a physicist at Simon Fraser University in Burnaby, as “the mantle is really what controls both to the rate of cooling of the planet.”

Drey and others say that the best way to catch mantle geoneutrinos would be from the ocean floor, where the crust is thinner than on land. One scheme, dubbed Hanako, would lower a 10,000-tonne detector down a hole, and has been on the drawing board for years. Construction alone would cost some US\$80 million to \$80 million, says John Learned, a neutrino physicist at the University of Hawaii at Manoa in Honolulu, and the technology is untested.

“We've never done anything like this before,” he says. But interest in the project is growing, he adds, and supporters are trying to drum up funds to keep it moving.

Meanwhile, China is working on its Daya Bay experiment, a 20,000-tonne detector on land that could be ready to hunt for geoneutrinos in 2018. Borexino has funds to run for at least another four years. And KamLAND plans to keep going for at least the next few years, says team member Hiroaki Nakamura of Tohoku University in Sendai, Japan. Even after Japan's nuclear reactors restart, the detector will still be able to find geoneutrinos — just not as easily. ■

1. Ratti, C. et al. *Nature* 488, 49–52 (2012).
2. Stange, T. et al. *Nature* 490, 49–52 (2012).
3. The Daya Bay Collaboration. Project at arxiv.org/abs/1301.4647 (2013).

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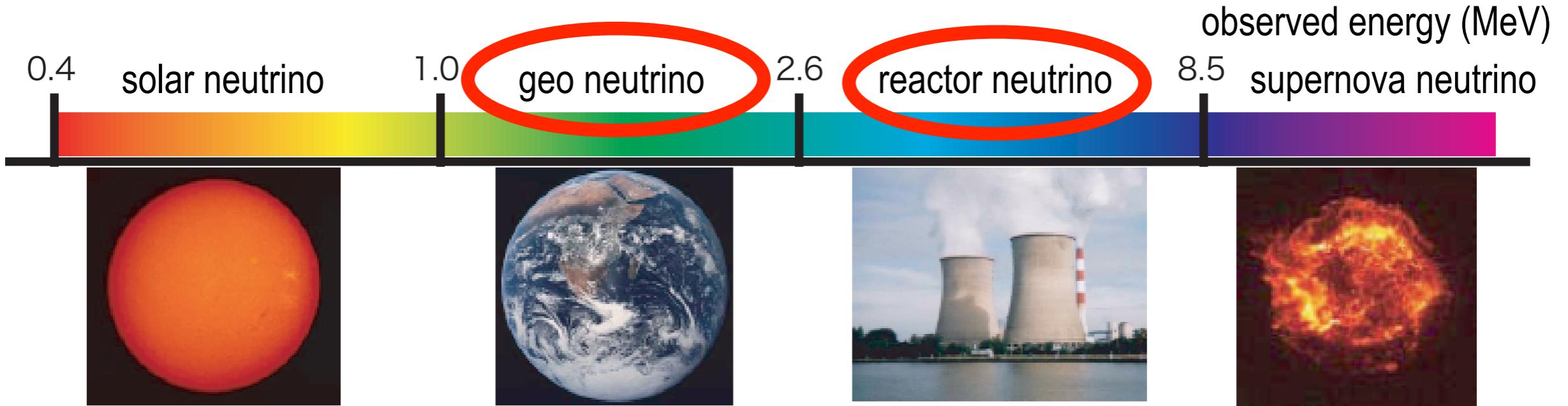
http://www.nature.com/polopoly_fs/1.12707!/menu/main/topColumns/topLeftColumn/pdf/496017a.pdf

Summary

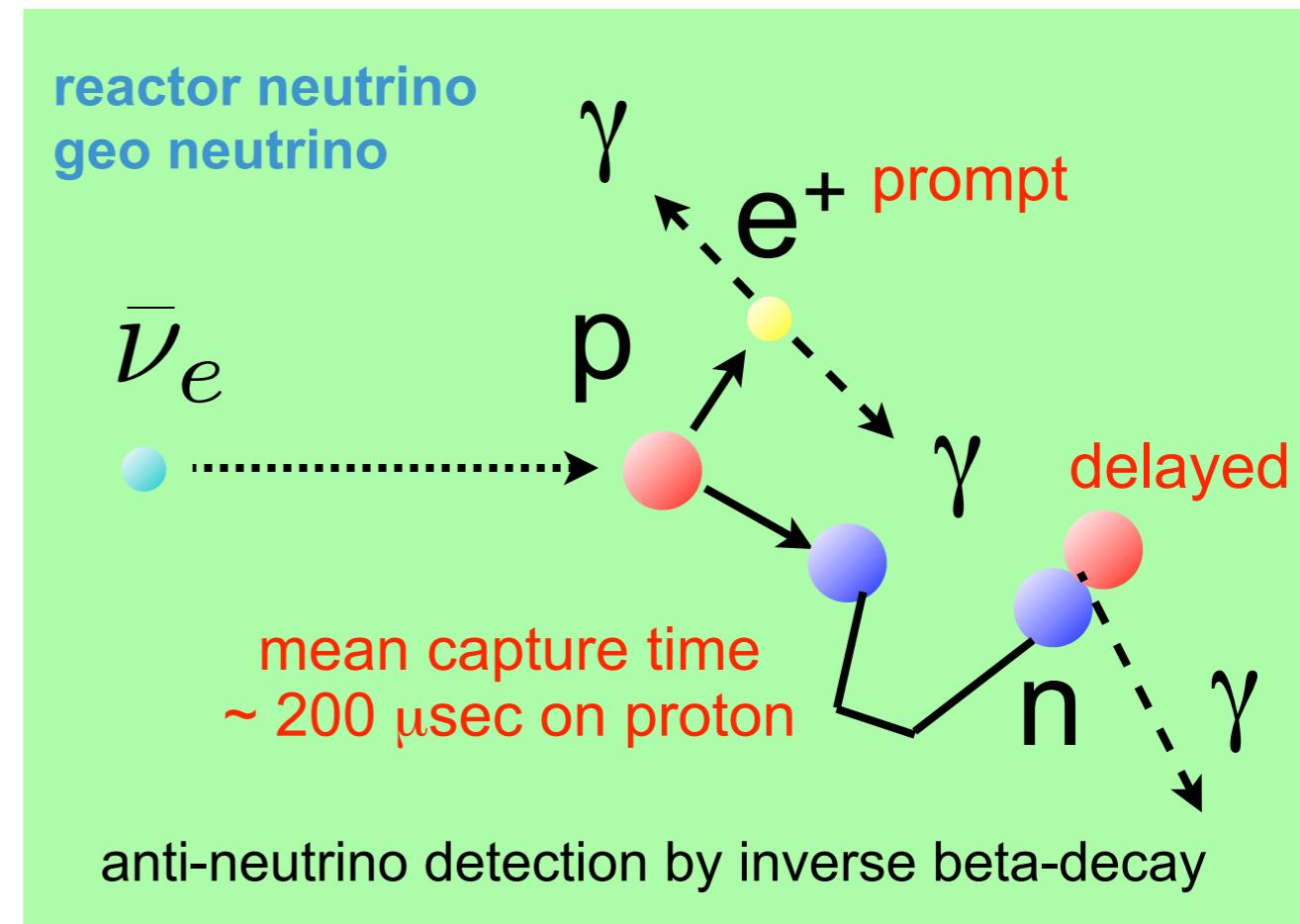
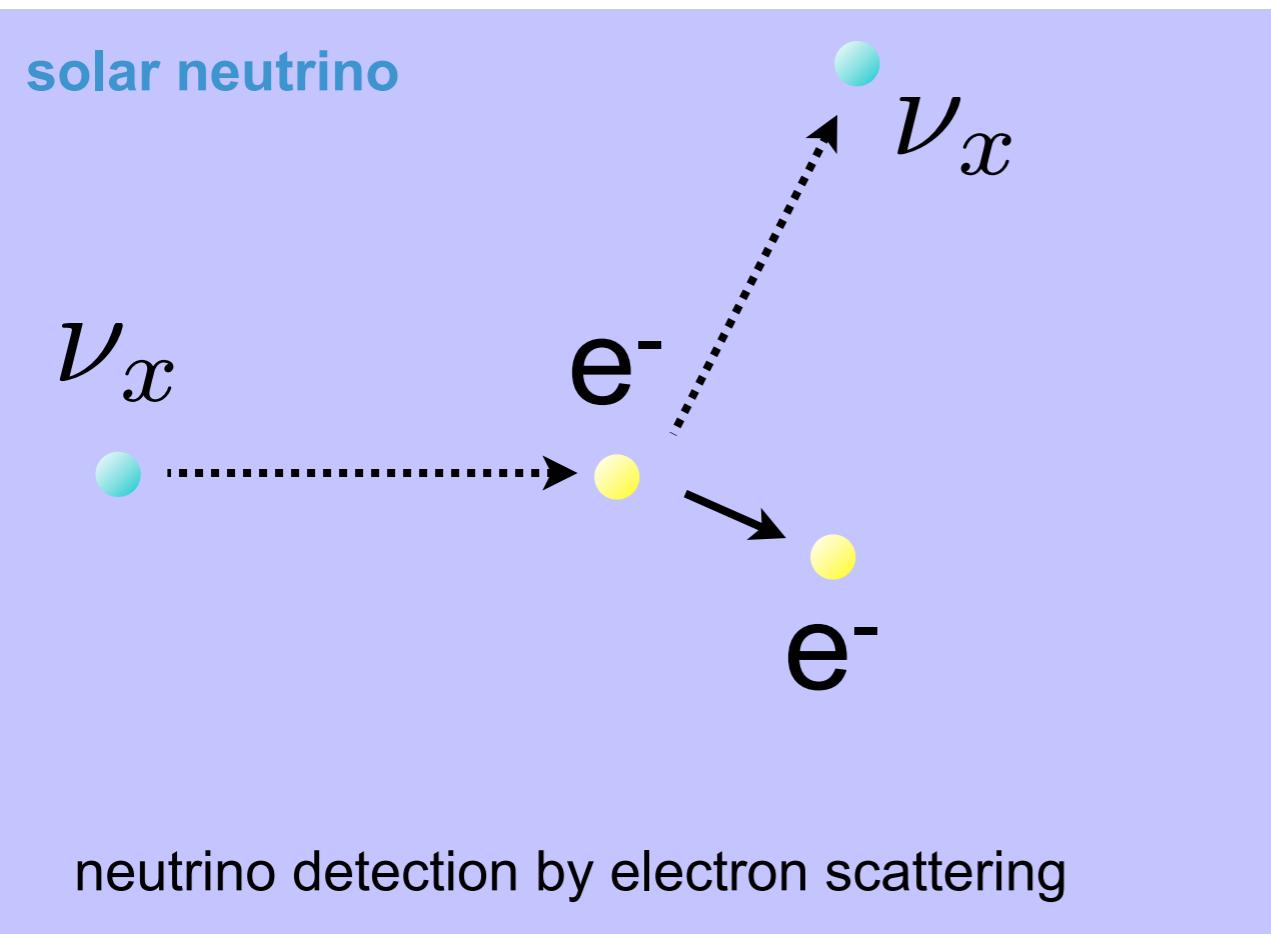
- Multi-site measurements by KamLAND and Borexino have just started.
- Geo neutrino experiments showed
 - Observed flux is still consistent with all BSE models
 - Radiogenic heat contributes only half of Earth's total heat flow → primordial heat still remain
- Tests of primitive meteorite and mantle convection model are the next target.
- Multi-site measurements at geologically different locations will be important for the tests.

Backup

Physics Target in KamLAND



Mar. 2013 new result (hep-ex/1303.4667)

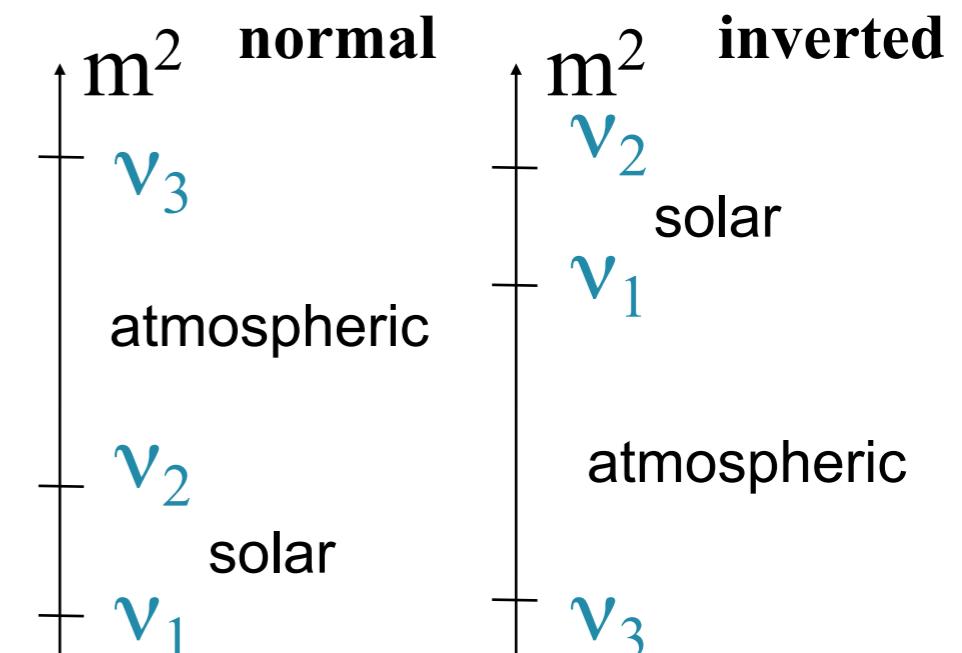


Neutrino Oscillation

MNS (Maki-Nakagawa-Sakata) Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\Delta m_{32}^2$$



θ_{23}	θ_{13} , CP phase			θ_{12}	Majorana phase
$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$	$\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}$	$\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$			
atmospheric			solar		

6 parameters : 3 mixing angle, 2 mass difference, 1 CP phase



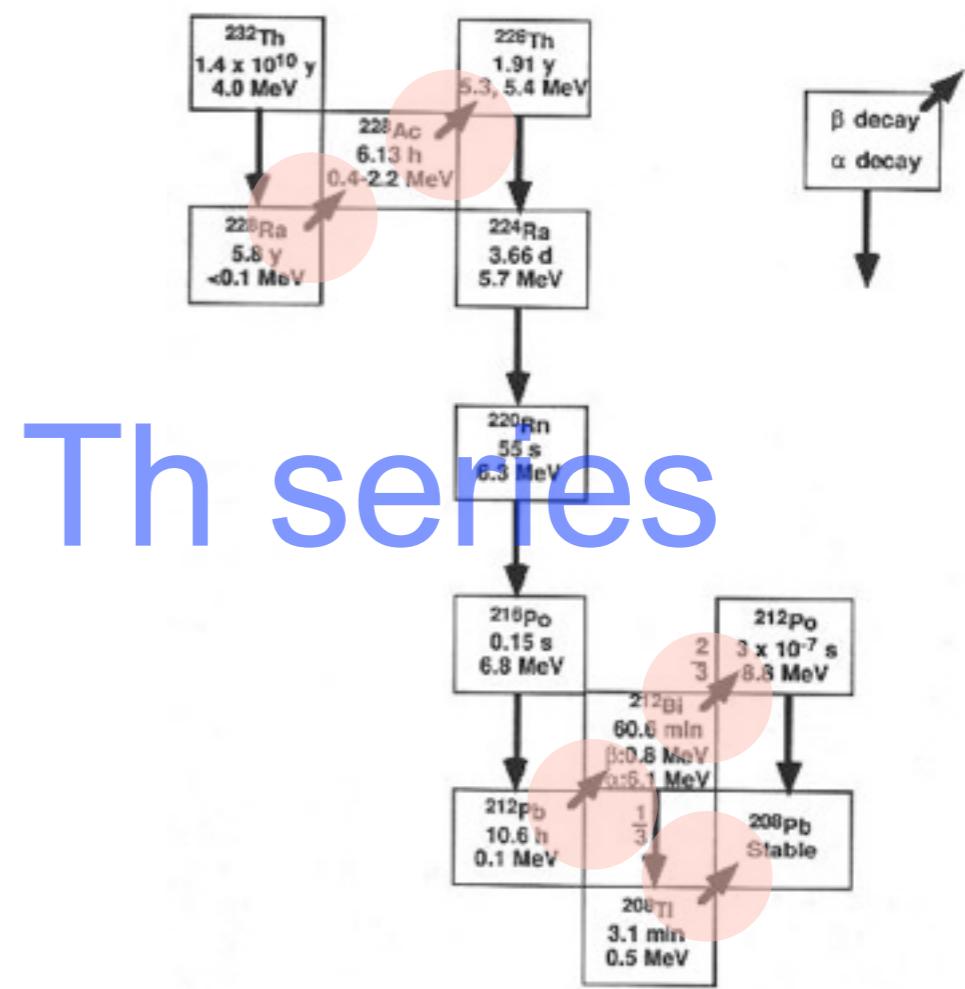
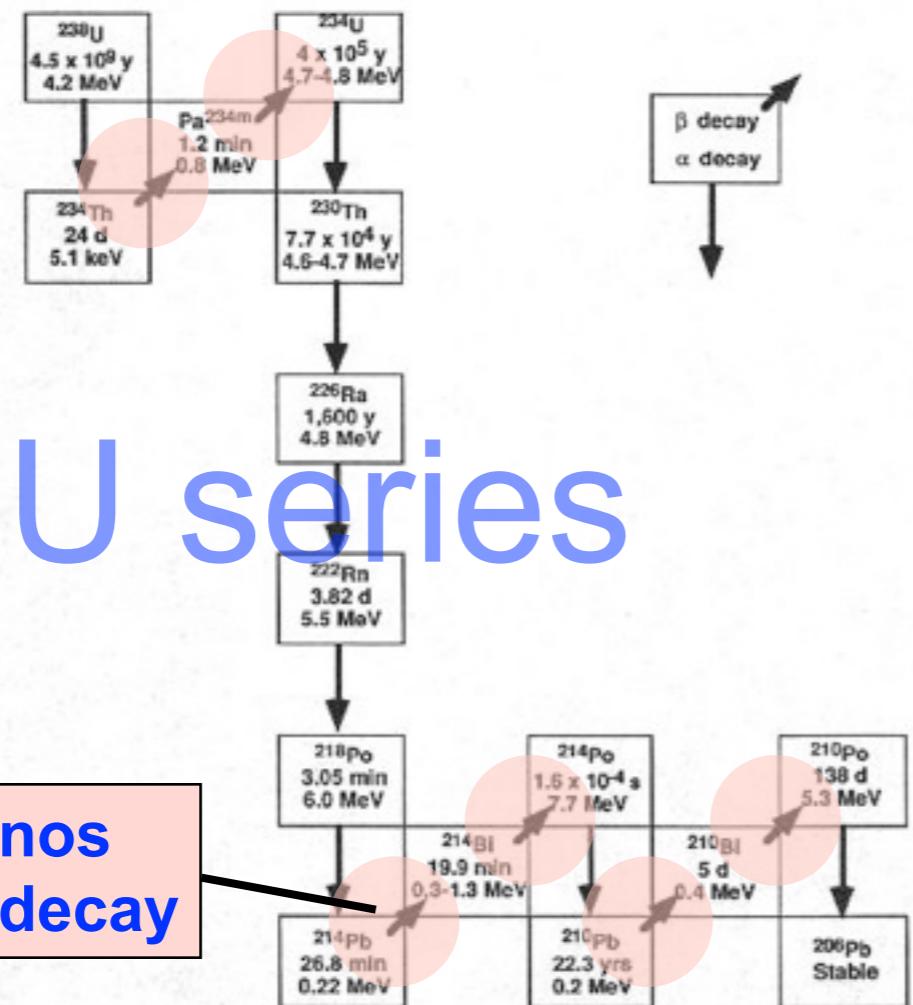
+ 2 Majorana phase

investigated by neutrino oscillation experiments
(solar, atmospheric, accelerator and reactor neutrinos)

Neutrino from the Earth

Heat sources in the Earth

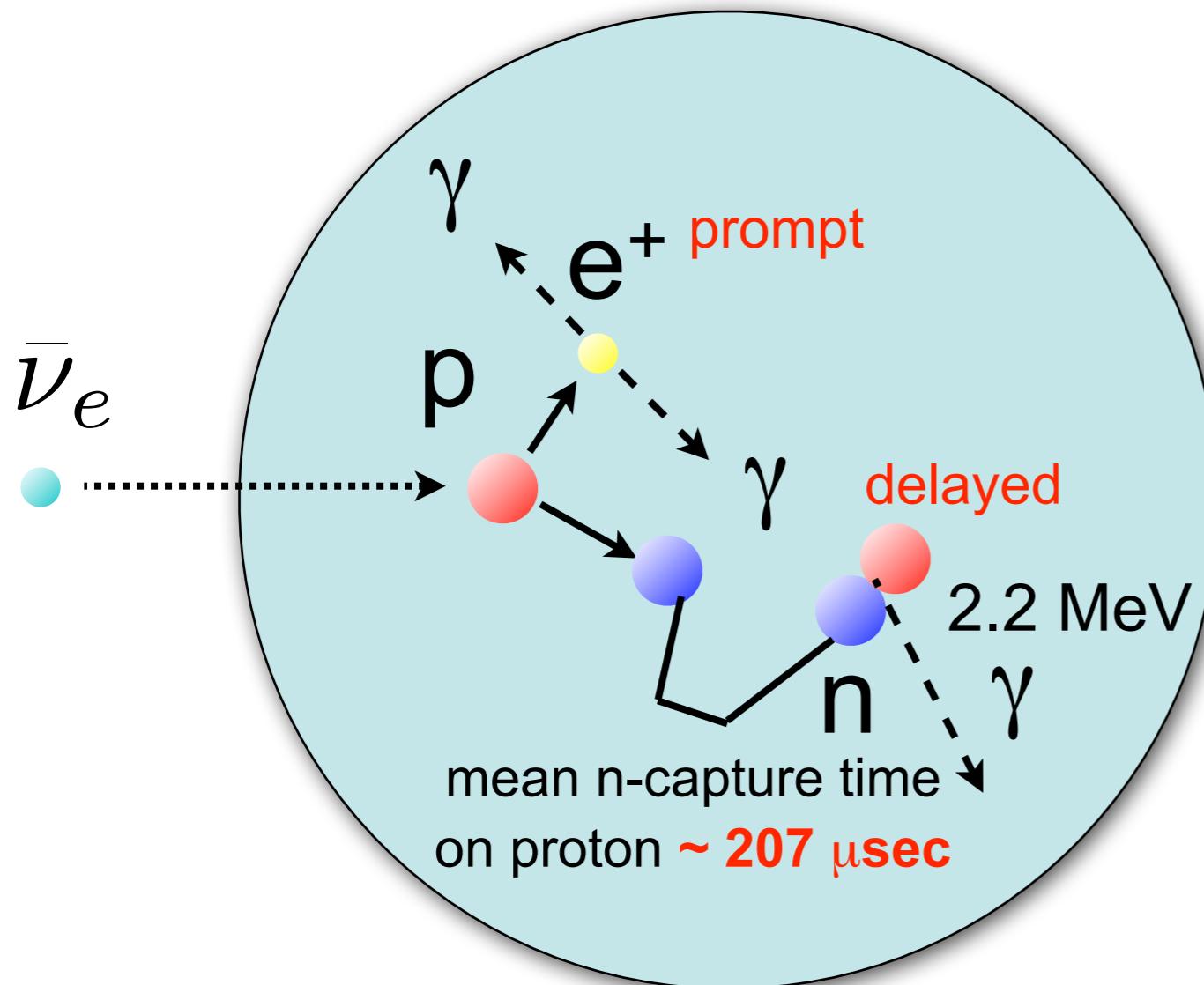
- (1) Radiogenic heat from U, Th, K decay
- (2) Release of gravitational energy through accretion or metallic core separation
- (3) Latent heat from the growth of inner core



Radiogenic heat : α -decay or β -decay emitting "anti-neutrinos"

Anti-Neutrino Detection

inverse beta-decay reaction



Tight background rejection
by delayed coincidence

(a) accidental B.G. discrimination

- $0.5 < \Delta T < 1000 \mu\text{s}$
- $\Delta R < 2 \text{ m}$
- $1.8 \text{ MeV} < E_{\text{delayed}} < 2.6 \text{ MeV}$ or $4.0 \text{ MeV} < E_{\text{delayed}} < 5.8 \text{ MeV}$
- $0.9 \text{ MeV} < E_{\text{prompt}} < 8.5 \text{ MeV}$
- $R_{\text{prompt}}, R_{\text{delayed}} < 6.0 \text{ m}$
- L-selection from 6 parameters

(b) μ spallation cut

- $\Delta T_\mu > 2 \text{ s}$ after showing μ
- $\Delta T_\mu > 2 \text{ s}$ or $\Delta L > 3 \text{ m}$ after non-showering μ ($\Delta Q < 10^6 \text{ p.e.}$)

Reactor and Geo Neutrino Analysis

previous result

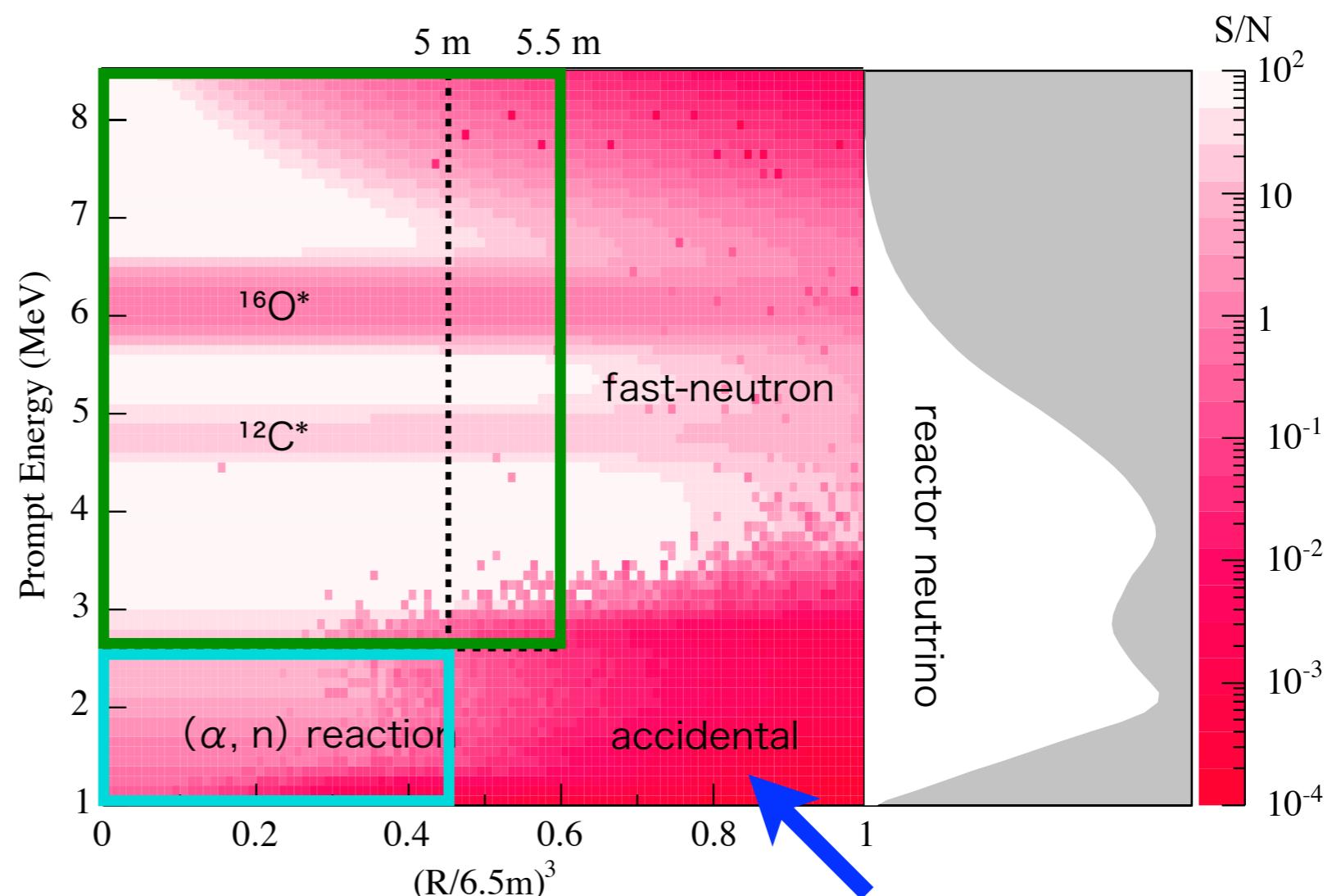
separated analysis
window for reactor
and geo neutrinos

reactor neutrino
(2.6 - 8.5 MeV, R 5.5 m)

geo neutrino
(0.9 - 2.6 MeV, R 5.0 m)



S / B ratio map (energy v.s. radius)



large accidental B.G.
caused by external γ -rays

Analysis improvement

- (1) efficient **accidental** background rejection
- (2) combined analysis of **reactor** and **geo neutrinos**

Anti-Neutrino Event Selection

(a) Accidental B.G. discrimination

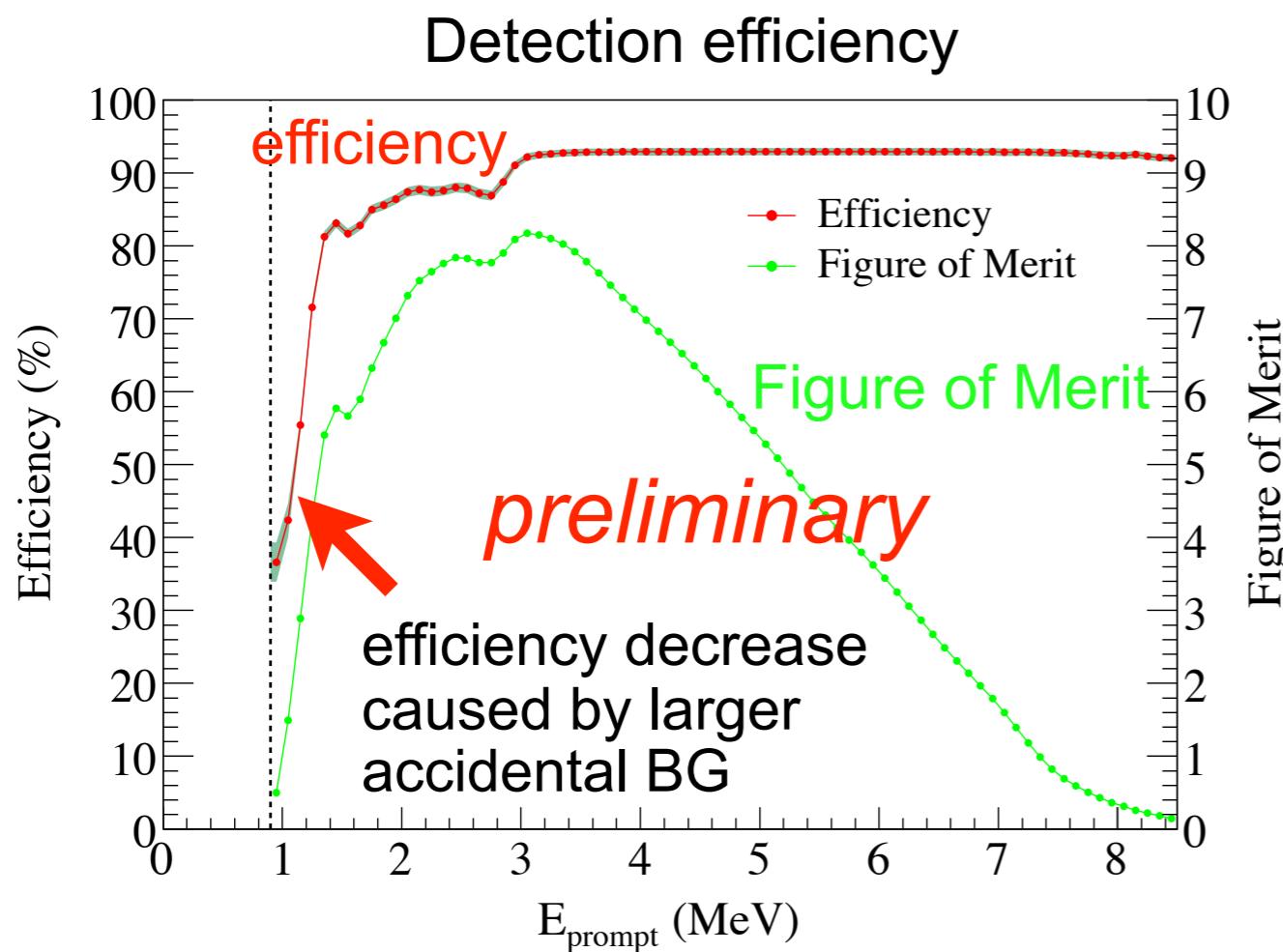
discriminator based on 5 parameters (E_d , ΔR , ΔT , R_p , R_d)

$$L_{\text{ratio}} = f_{\bar{\nu}} / (f_{\bar{\nu}} + f_{\text{accidental}}) \quad f : \text{PDF}$$

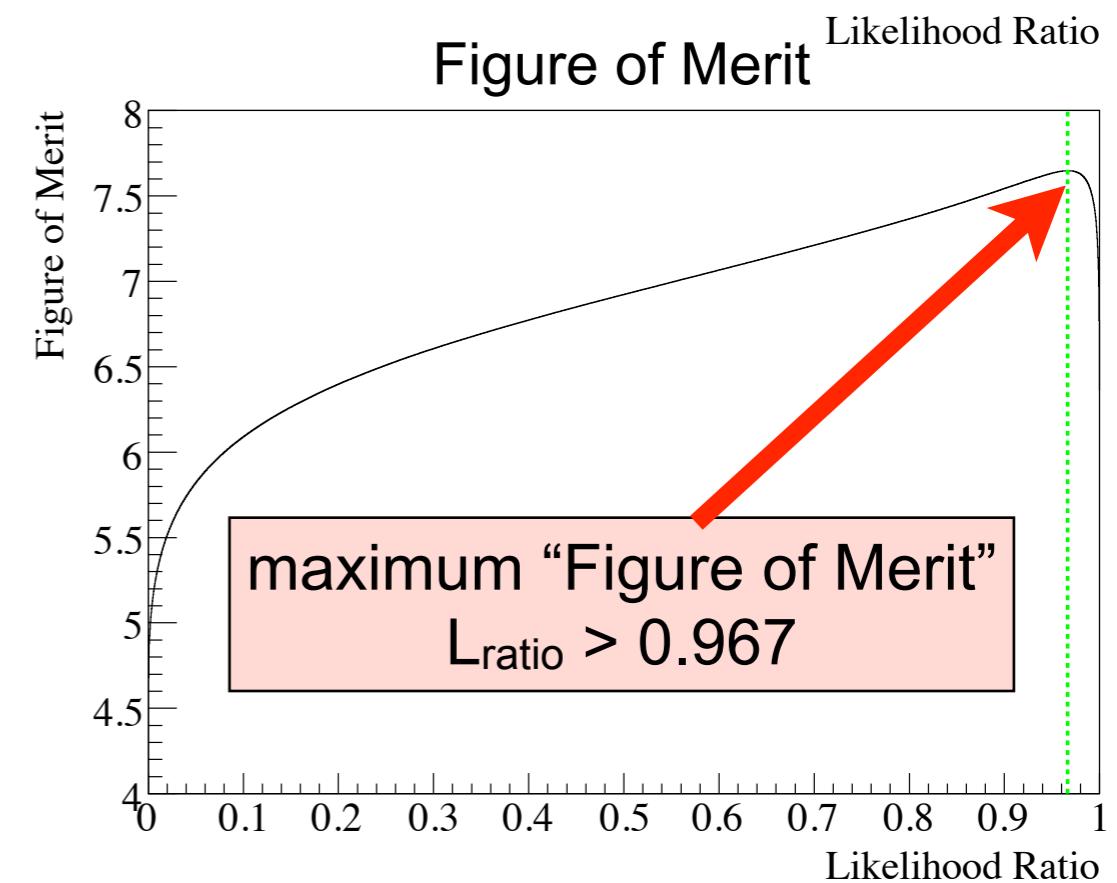
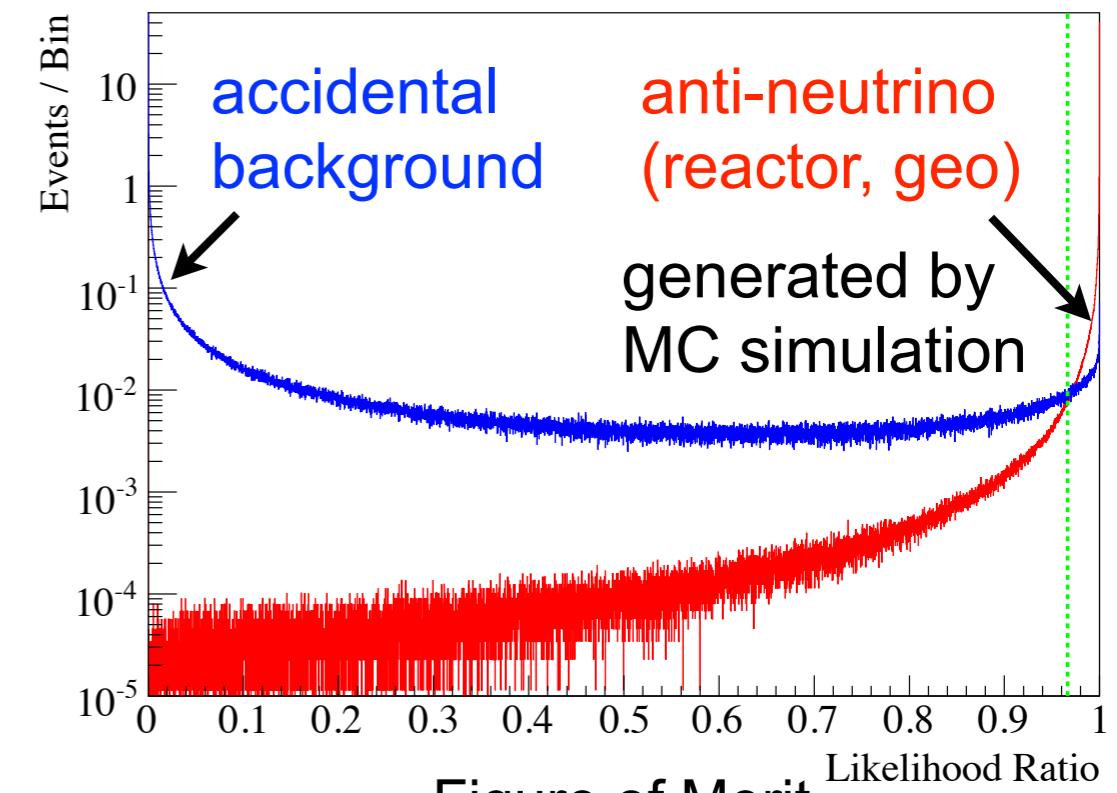
Selection : Maximize "Figure of Merit" $\frac{S}{\sqrt{S + B_{\text{accidental}}}}$

(b) μ spallation cut

- $\Delta T_\mu > 2$ s after showing μ ($\Delta Q > 10^6$ p.e.)
- $\Delta T_\mu > 2$ s or $\Delta L > 3$ m after non-showering μ



$2.2 < E_{\text{prompt}} < 2.3$ MeV

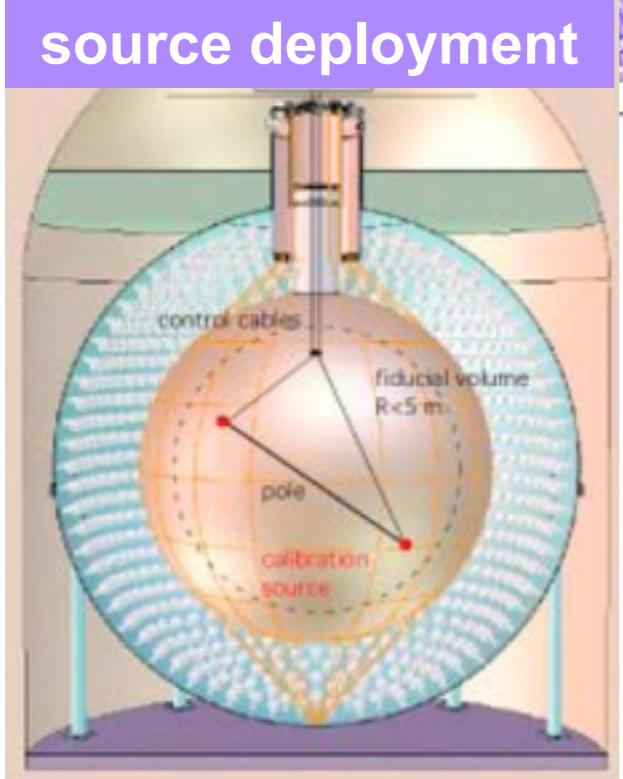
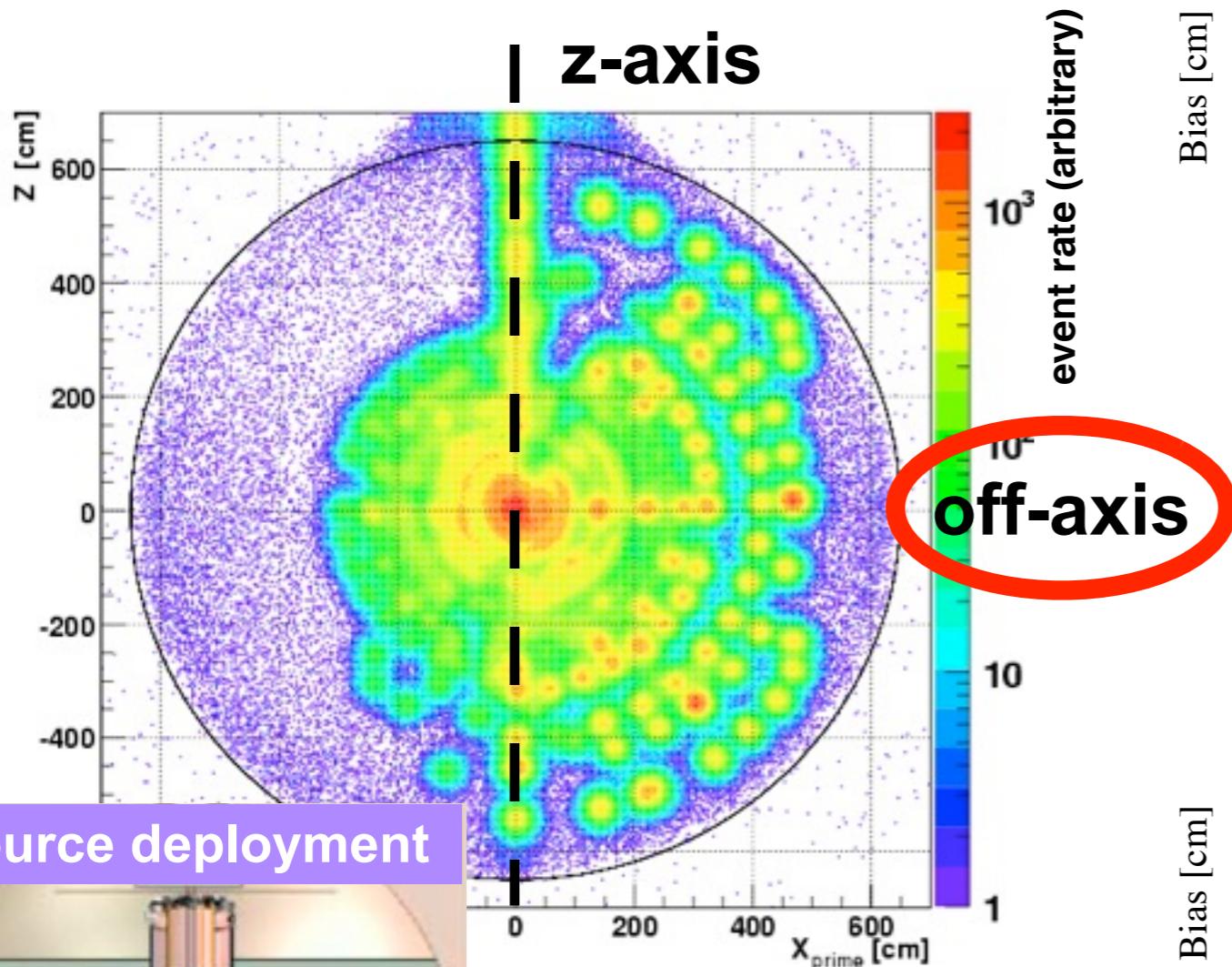


Systematic Uncertainty

before / after purification

		Detector-related (%)	Reactor-related (%)	
Δm_{21}^2	Energy scale	1.8 / 1.8	$\bar{\nu}_e$ -spectra [21]	0.6 / 0.6
Rate	Fiducial volume	1.8 / 2.5	$\bar{\nu}_e$ -spectra	1.4 / 1.4
	Energy scale	1.1 / 1.3	Reactor power	2.1 / 2.1
	$L_{cut}(E_p)$ eff.	0.7 / 0.8	Fuel composition	1.0 / 1.0
	Cross section	0.2 / 0.2	Long-lived nuclei	0.3 / 0.4
	Total	2.3 / 3.0	Total	2.7 / 2.8

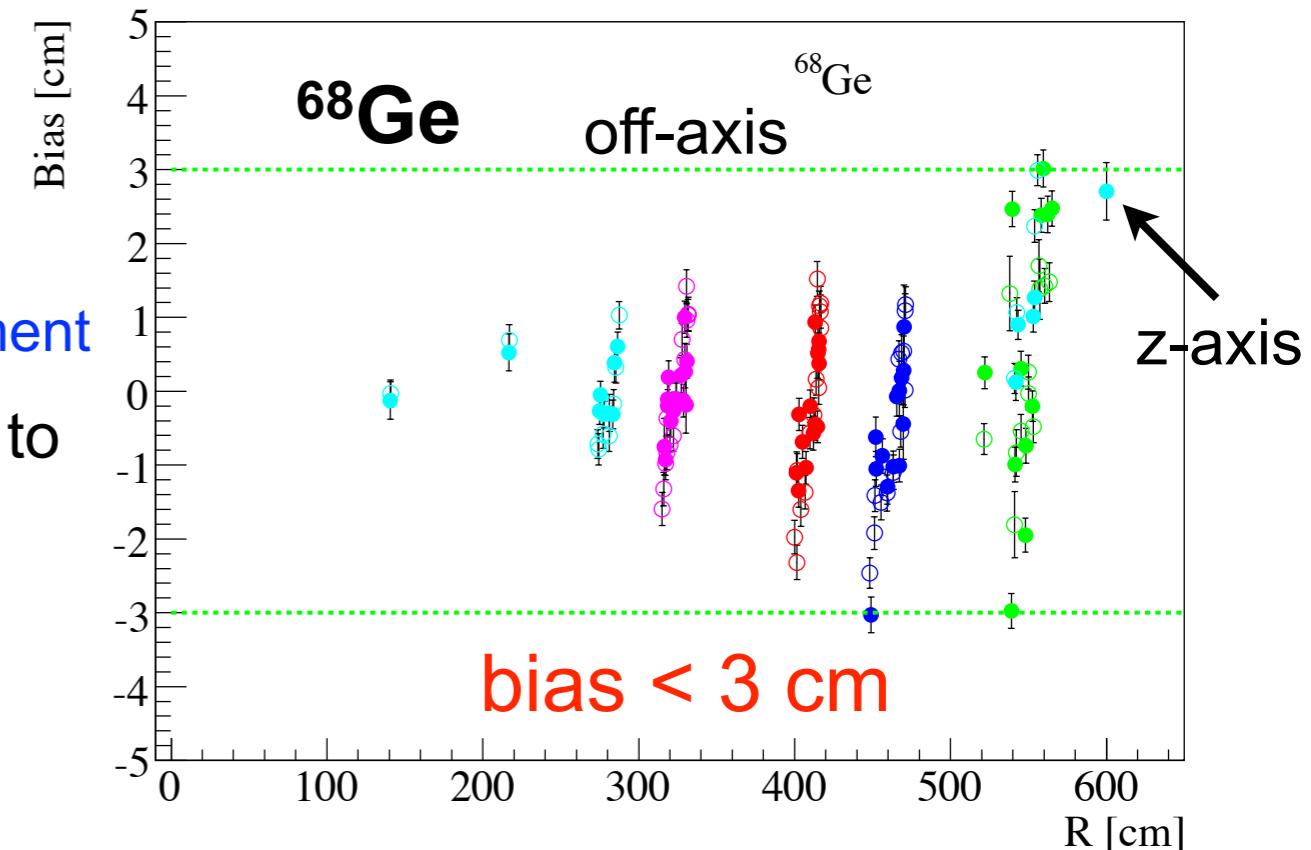
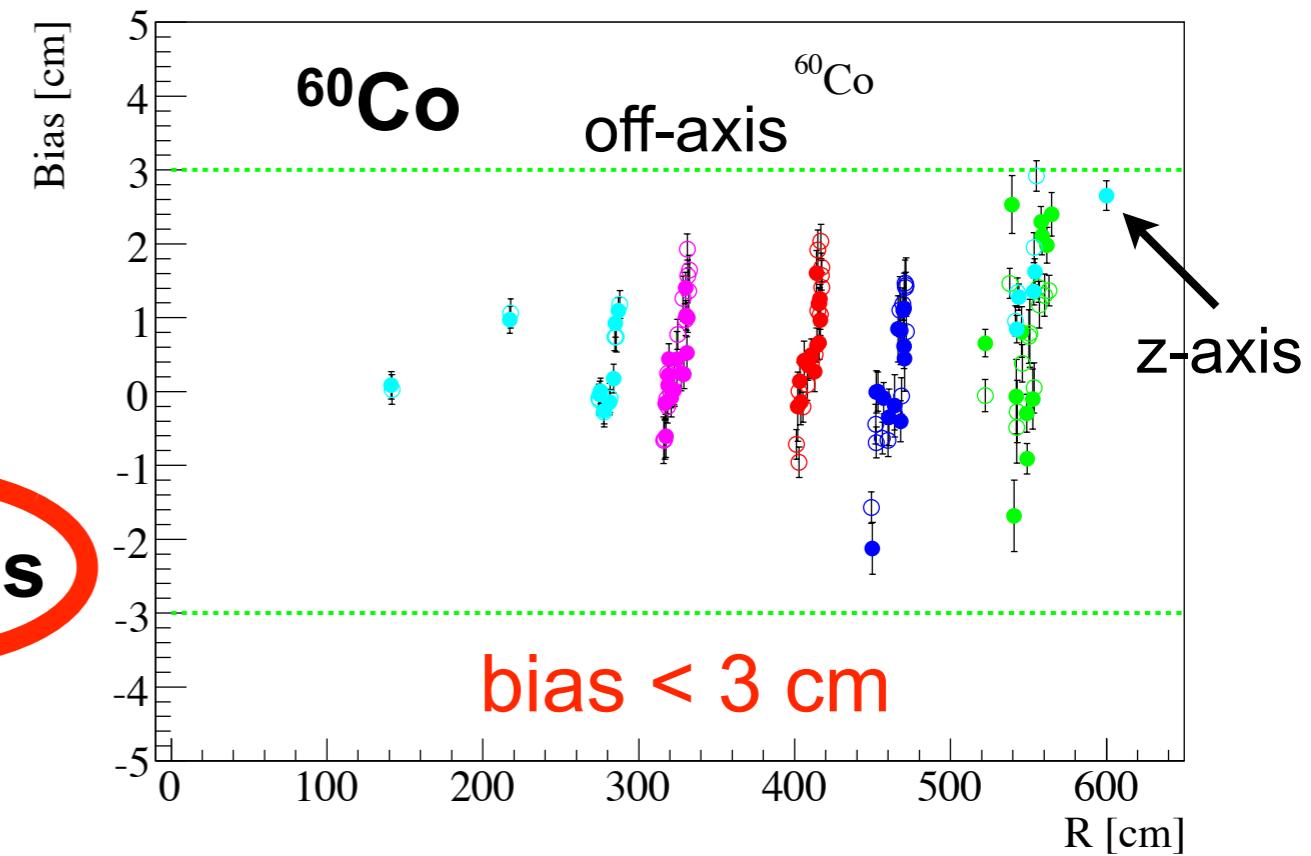
Full Volume Calibration

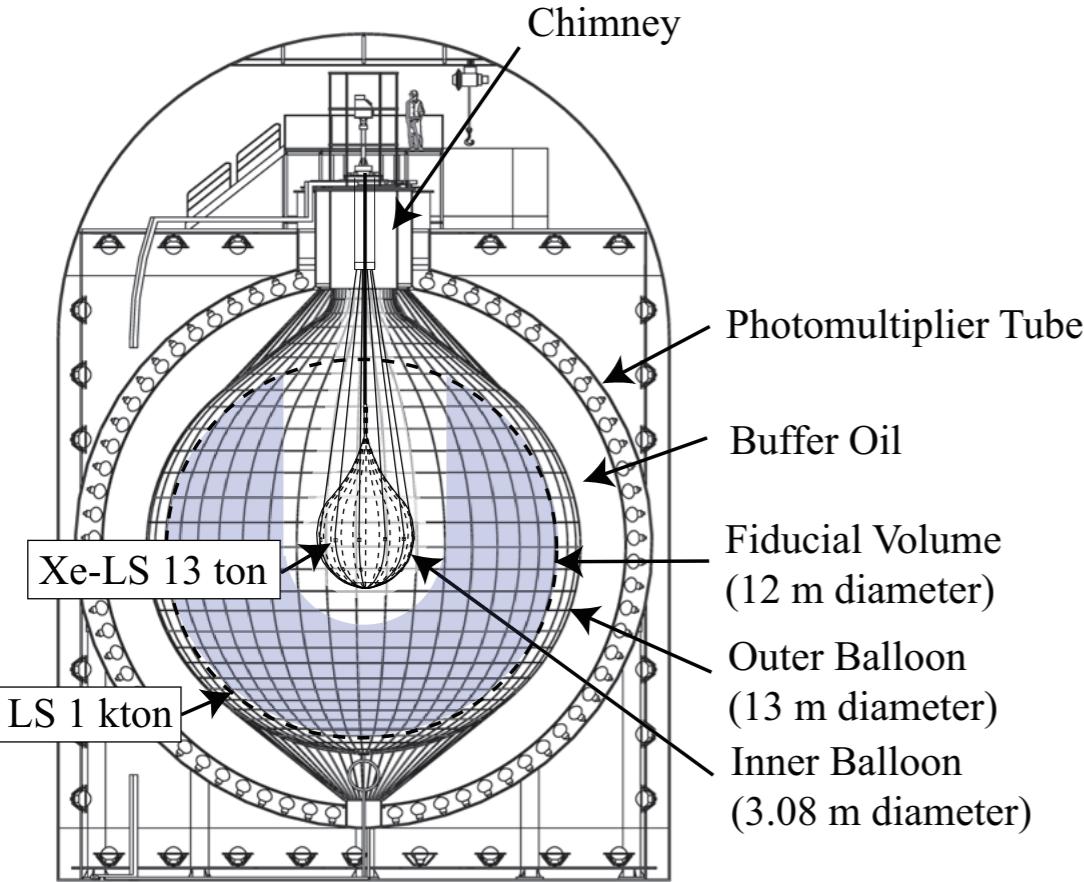


“4pi calibration” system for
the off-axis source deployment

bias < 3 cm corresponds to
1.8% volume uncertainty

cross-checked by
 $^{12}\text{B}/^{12}\text{N}$ uniformity



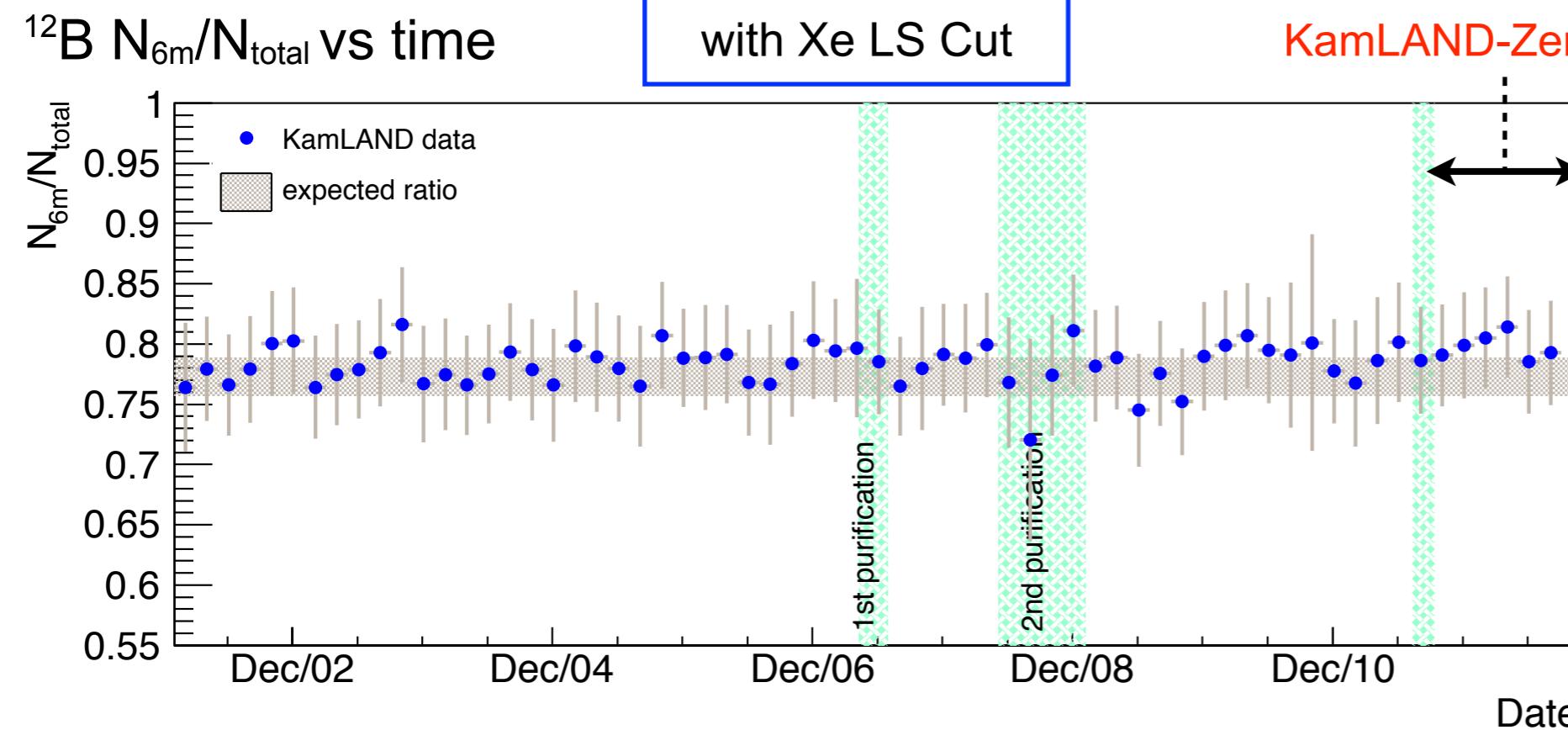


- Vertex cut conditions

To minimize accidental coincidences, we apply **Xe LS cut** for KamLAND-Zen Phase in $R < 6.0\text{m}$ fiducial volume.

$R > 2.5\text{m}$, cylinder cut ($\rho > 2.5\text{m}$, $Z > 0$)
(cut out volume 16.6% of $R < 6\text{m}$)

- Data stability of KamLAND region

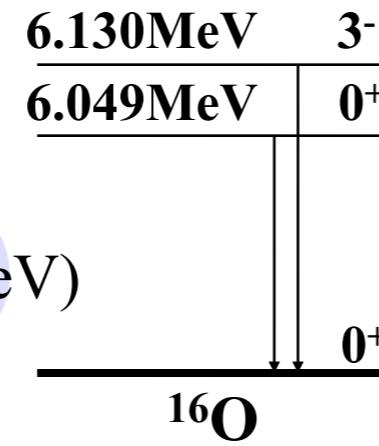
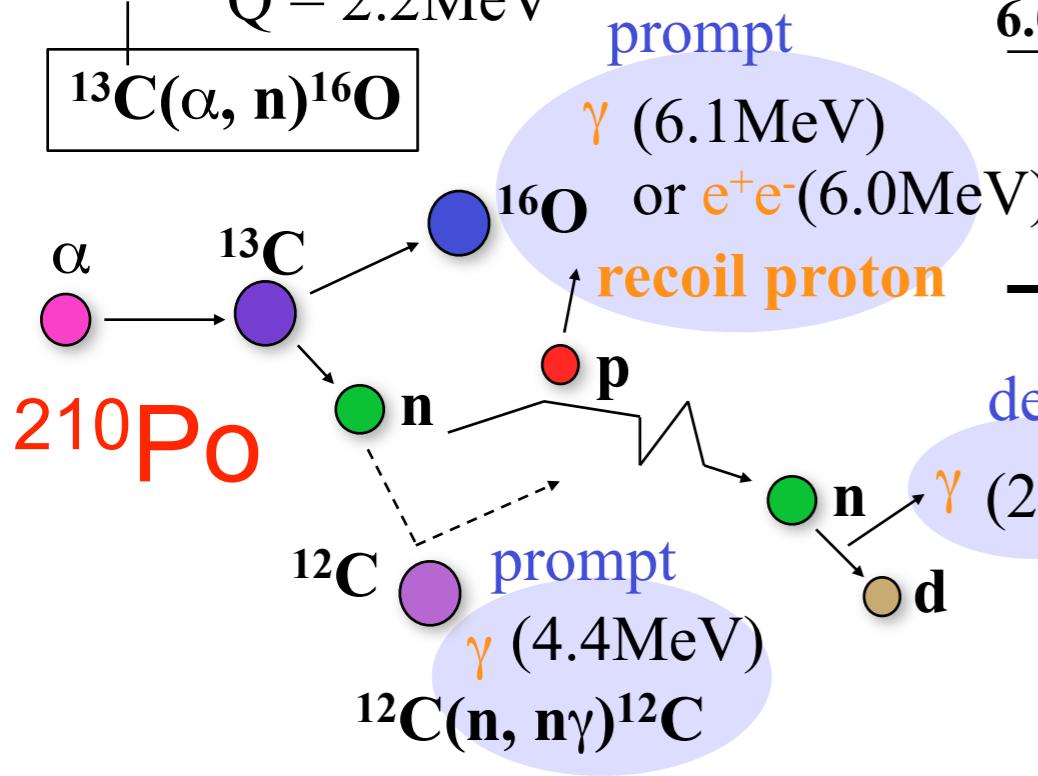


- Event rate has been stable.
- difference before and after purification : **2.5%**

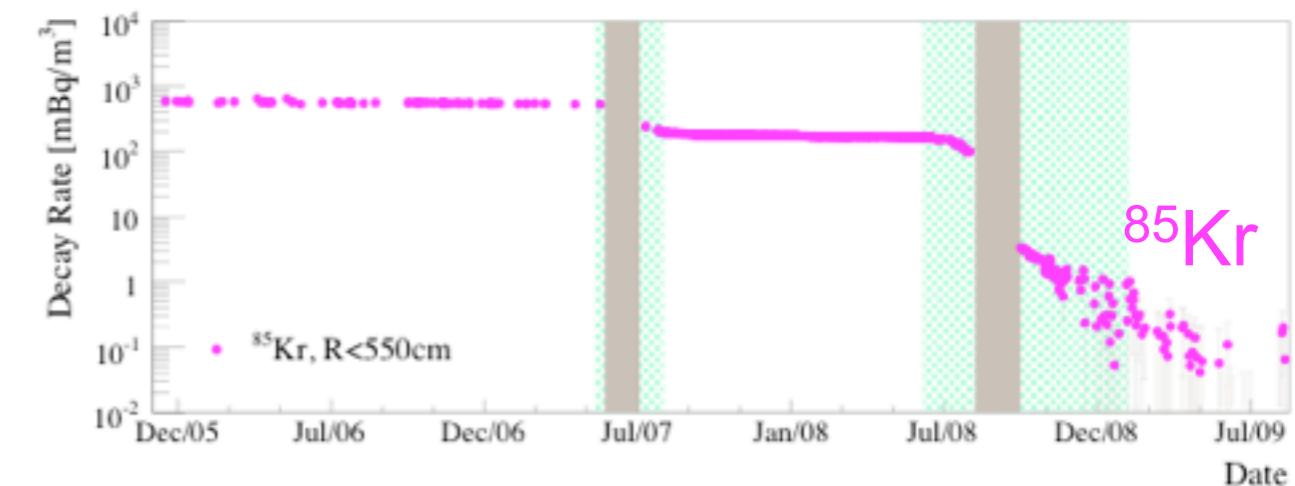
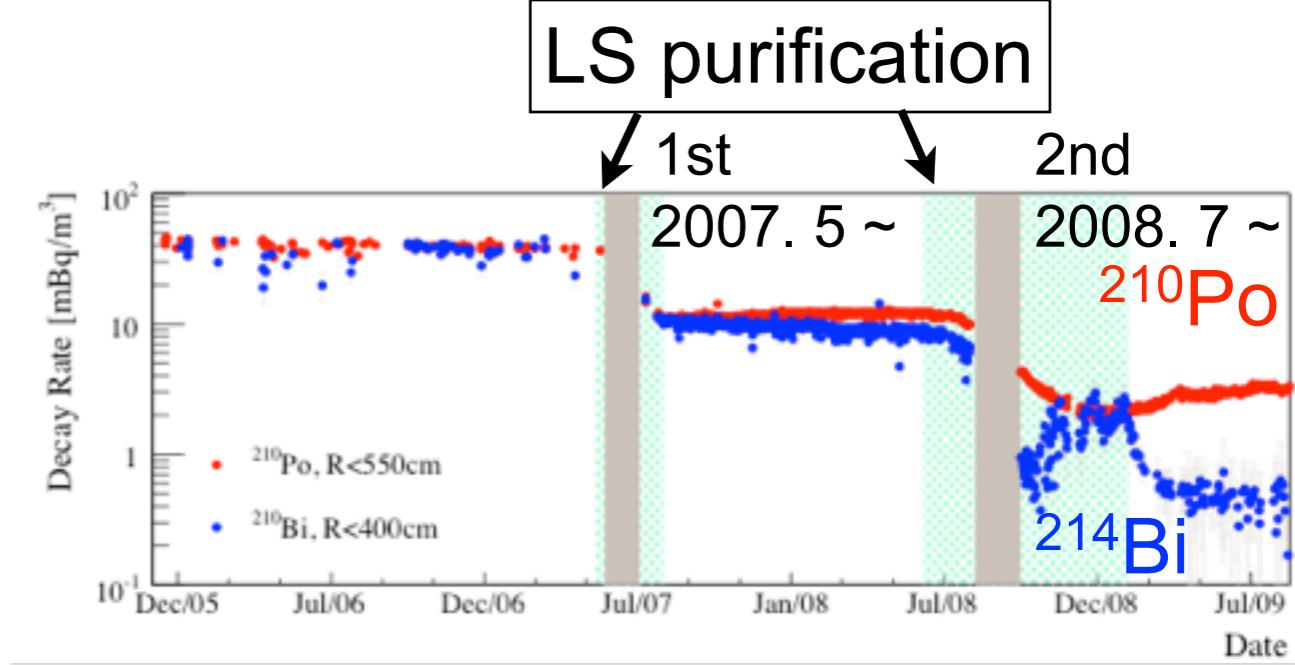
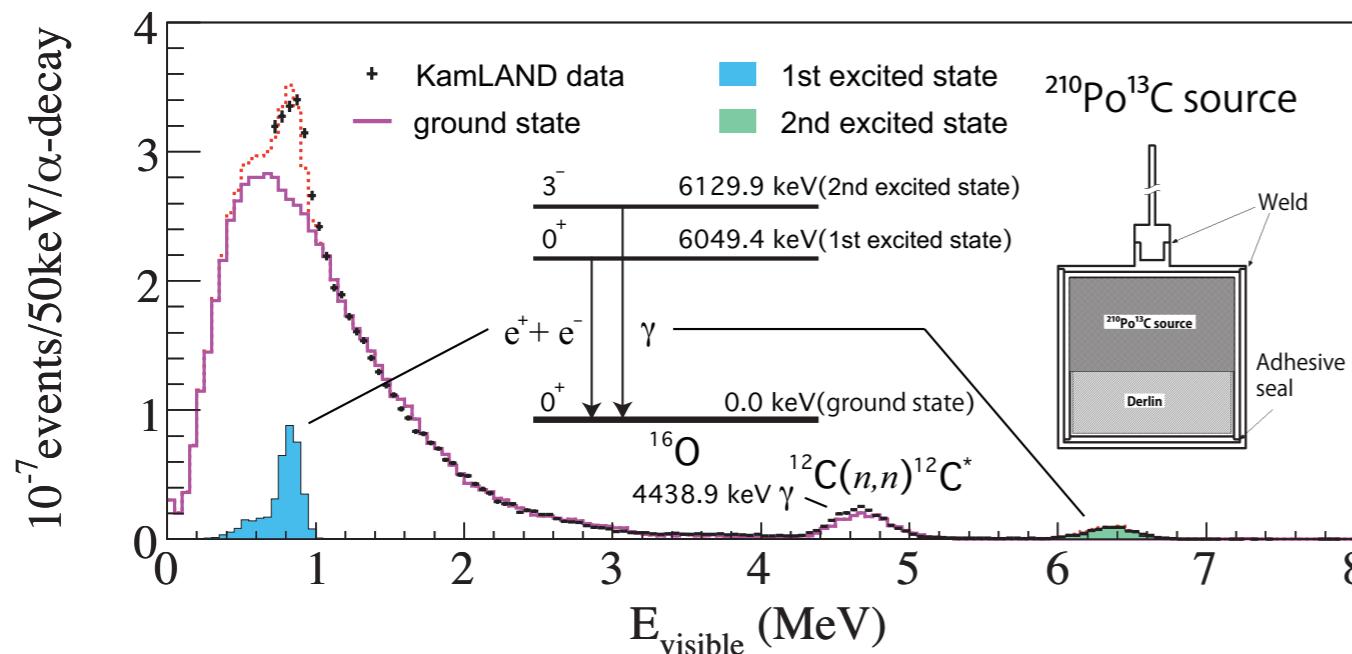
Background Estimation

natural abundance

$$1.1\% \quad Q = 2.2 \text{ MeV}$$



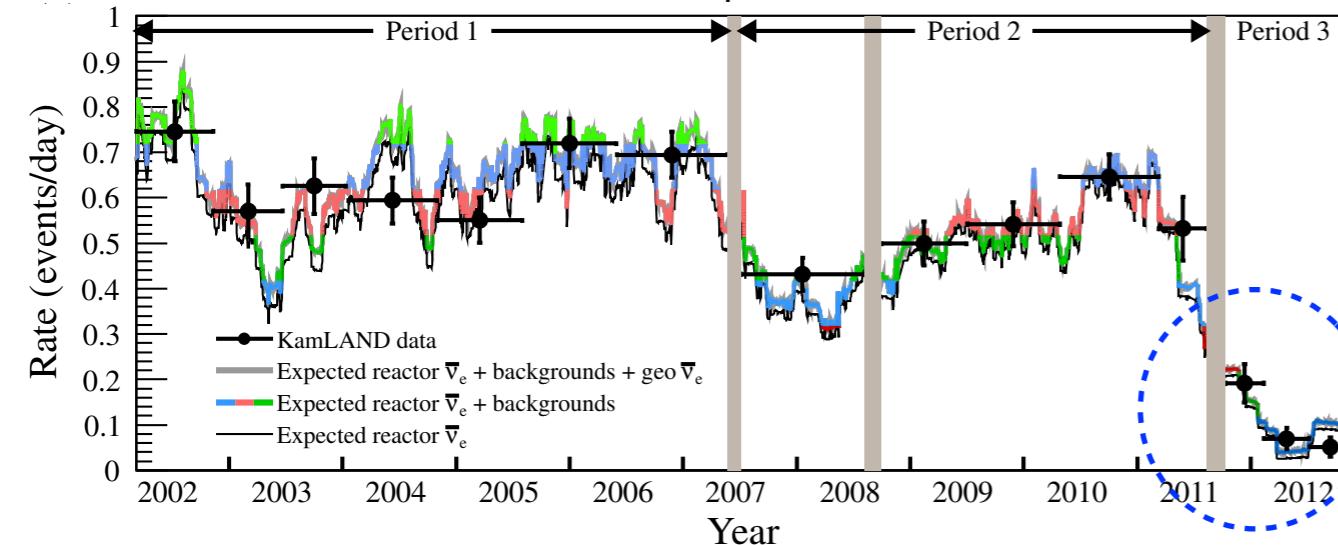
in-situ calibration with $^{210}\text{Po}^{13}\text{C}$



- (1) dominant BG source (α, n) has been reduced by down to $\sim 1/20$
 - (2) determination of the cross section is improved by in-situ calibration
- uncertainty: **11%** for ground state

Correlation Plot

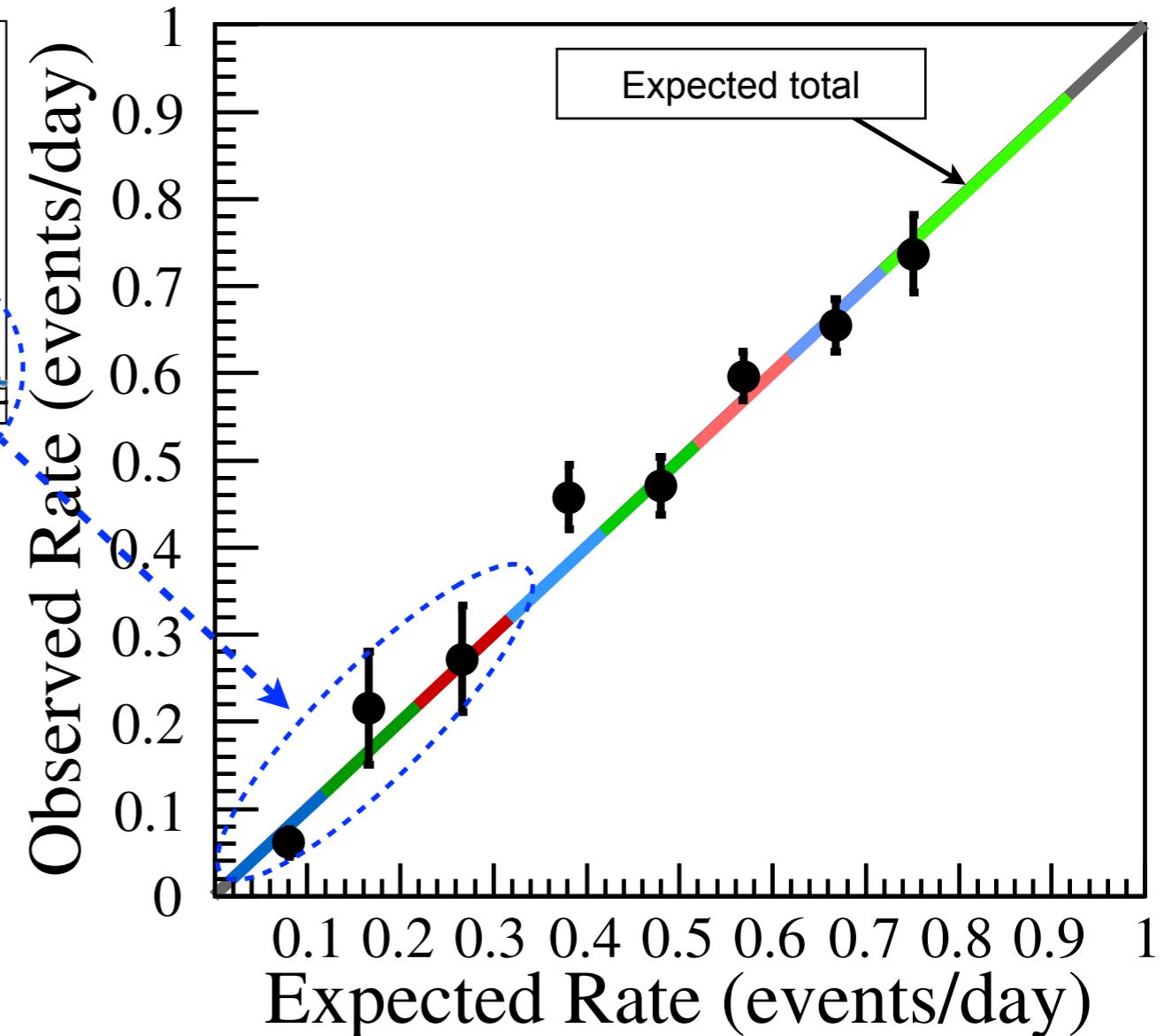
$$2.6 < E_p < 8.5 \text{ MeV}$$



**provide good data to
confirm our background**



“Rate + Shape + Time” analysis



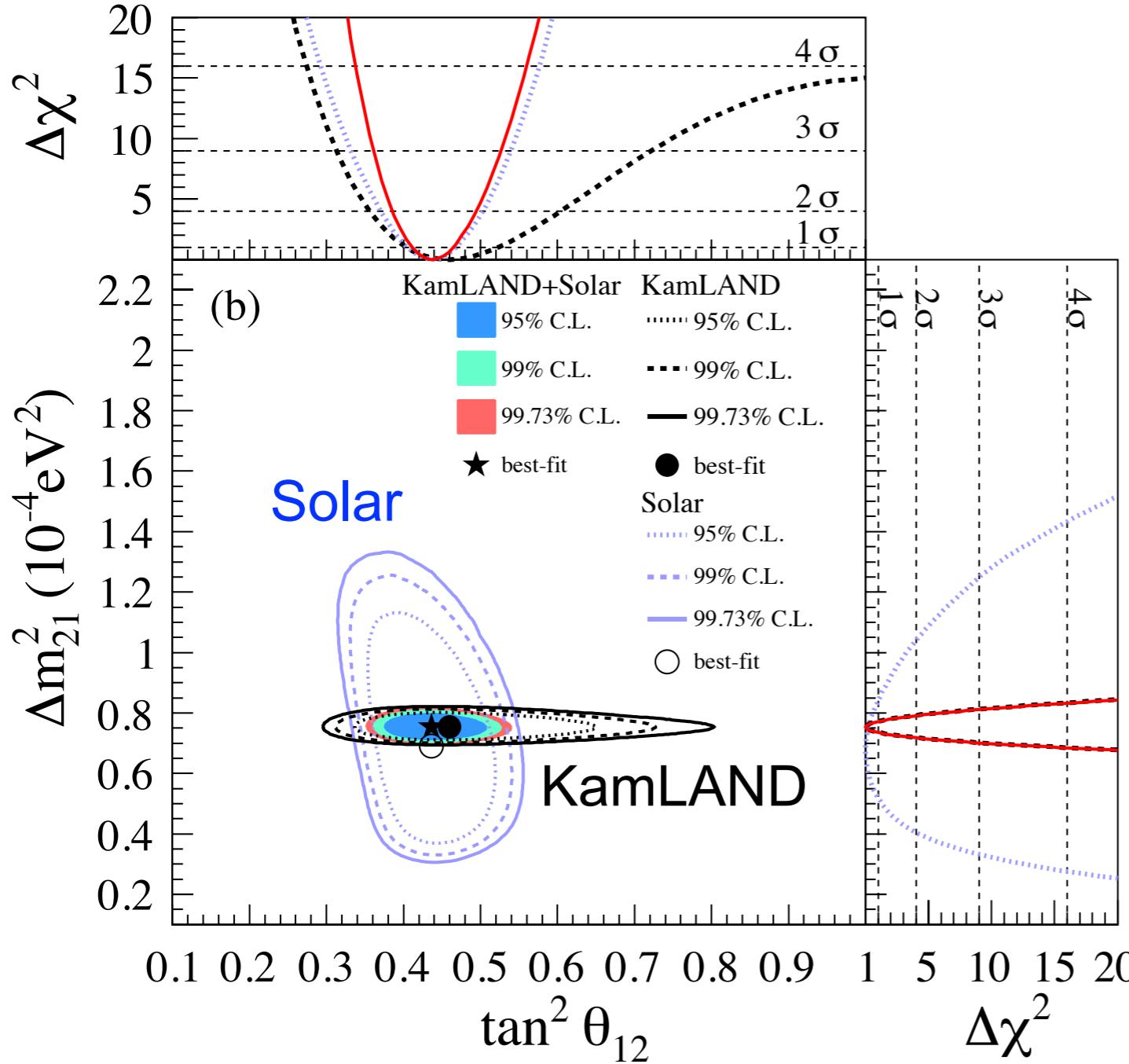
$$\begin{aligned} \chi^2 = & \chi_{\text{rate}}^2(\theta_{12}, \theta_{13}, \Delta m_{21}^2, N_{\text{BG}1 \rightarrow 5}, N_{\text{U,Th}}^{\text{geo}}, \alpha_{1 \rightarrow 4}) \\ & - 2 \ln \underline{L_{\text{shape}}}(\theta_{12}, \theta_{13}, \Delta m_{21}^2, N_{\text{BG}1 \rightarrow 5}, N_{\text{U,Th}}^{\text{geo}}, \alpha_{1 \rightarrow 4}) \\ & + \chi_{\text{BG}}^2(N_{\text{BG}1 \rightarrow 5}) + \chi_{\text{syst}}^2(\alpha_{1 \rightarrow 4}) \\ & + \chi_{\text{osci}}^2(\theta_{12}, \theta_{13}, \Delta m_{21}^2) . \end{aligned}$$

time dependent

3-Flavor Oscillation Parameters

θ_{12} : Solar constraint is dominant

Δm^2 : KamLAND constraint is dominant



survival probability

$$P_{ee}^{3\nu} = \cos^4 \theta_{13} P_{e'e'}^{2\nu} + \sin^4 \theta_{13}$$

\downarrow electron density

matter effect

$$N_{e'} \rightarrow N_e \cos^2 \theta_{13}$$

atmospheric oscillation length
is completely averaged out

~~Δm^2_{31}~~

solar + KamLAND + θ_{13} experiments

$$\begin{aligned} \Delta m^2_{21} &= 7.53^{+0.18}_{-0.18} \times 10^{-5} \text{ eV}^2 \\ \tan^2 \theta_{12} &= 0.436^{+0.029}_{-0.025} \\ \sin^2 \theta_{13} &= 0.023^{+0.002}_{-0.002} \end{aligned}$$

Reference Earth Model

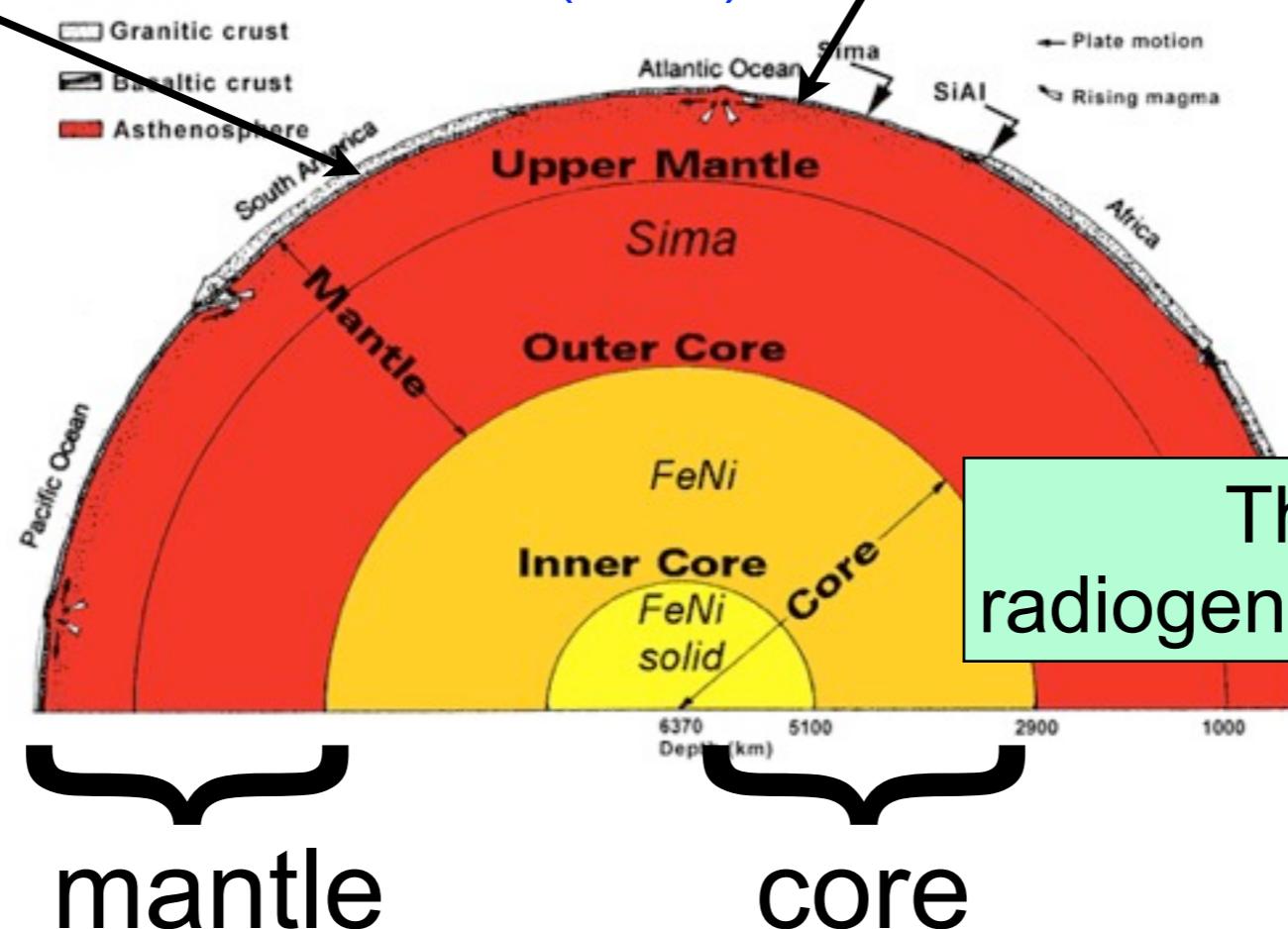
UCC U : 2.8 ppm / Th : 10.7 ppm

MCC U : 1.6 ppm / Th : 6.1 ppm

LCC U : 0.2 ppm / Th : 1.2 ppm

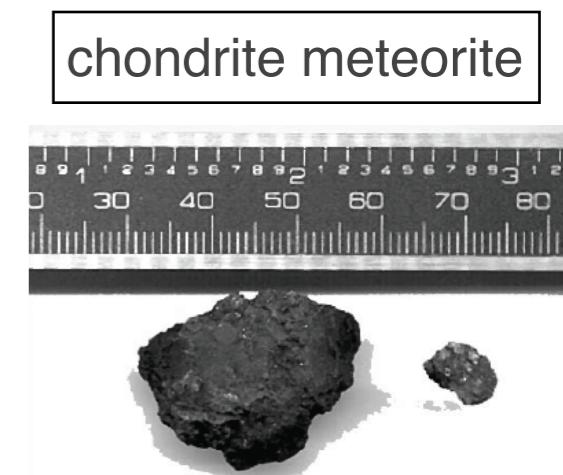
continental
crust

Rudnick et al. (1995)



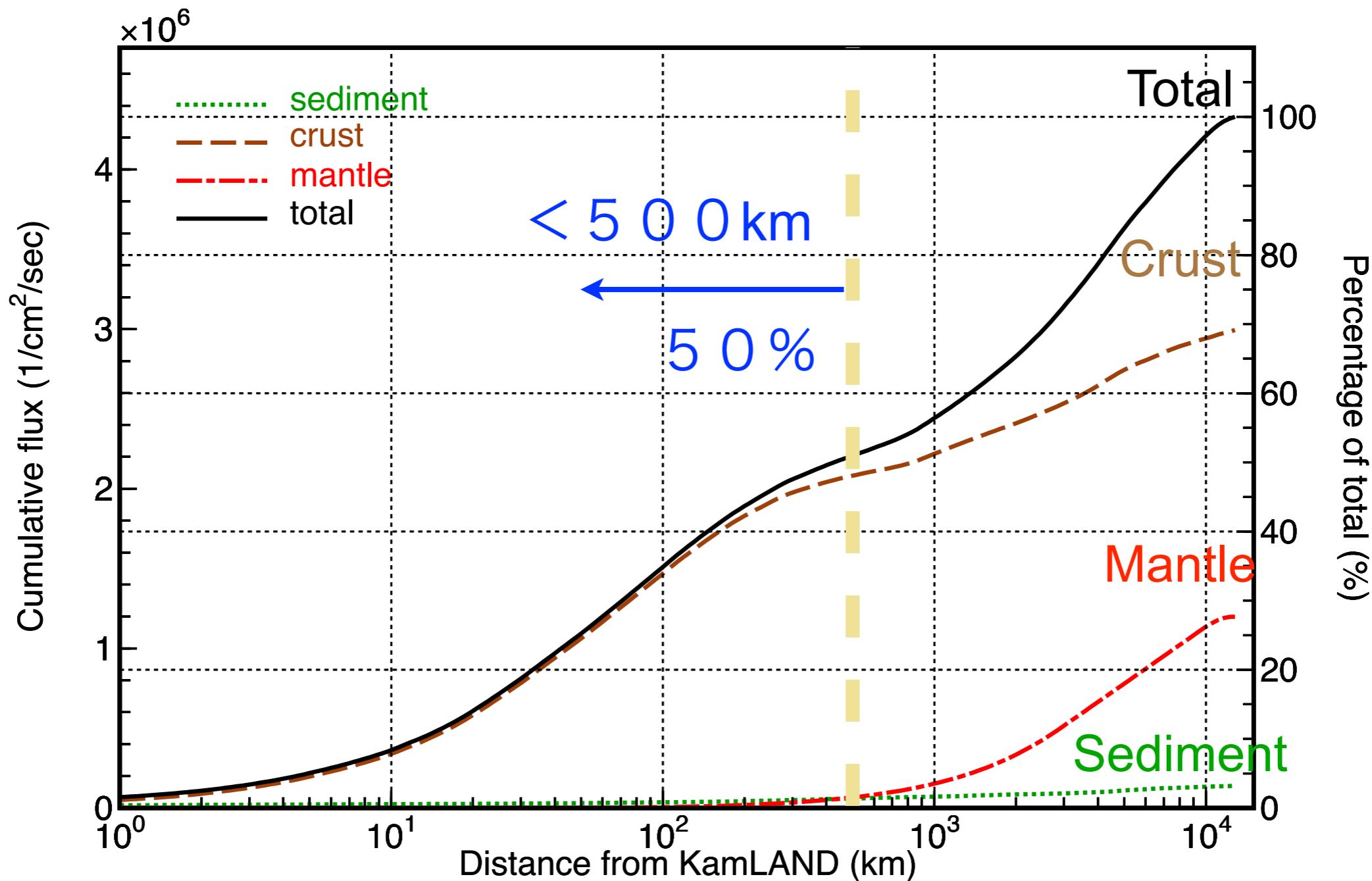
U : 0.012 ppm / Th : 0.048 ppm

U : 0 ppm / Th : 0 ppm
no U/Th in core



Mantle = BSE (Primitive Mantle) – Crust

Distance and Cumulative Flux

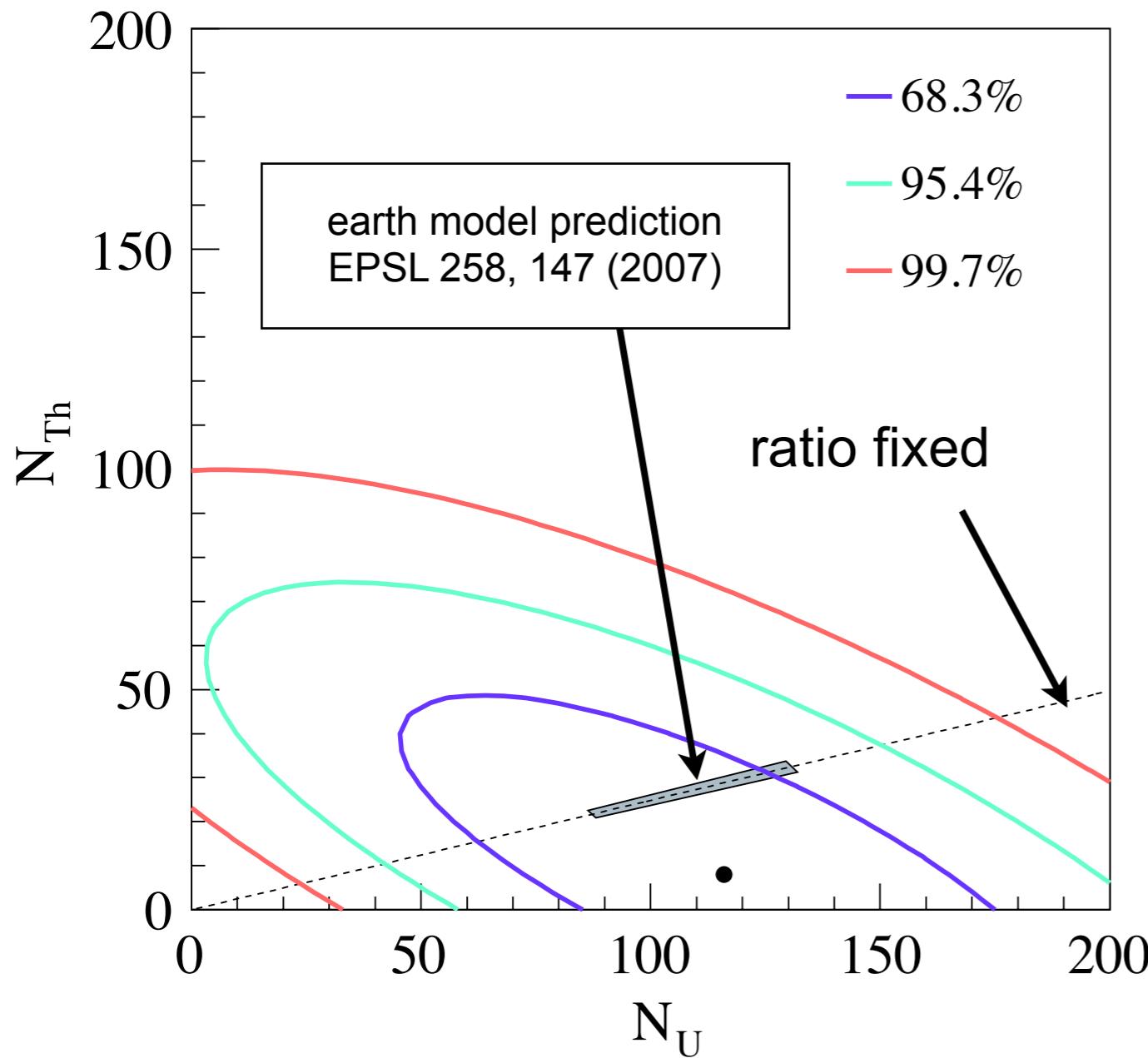


neutrino oscillation

$$P(E, L) \sim 1 - \frac{1}{2} \sin^2 2\theta_{12} \quad (\text{constant suppression})$$

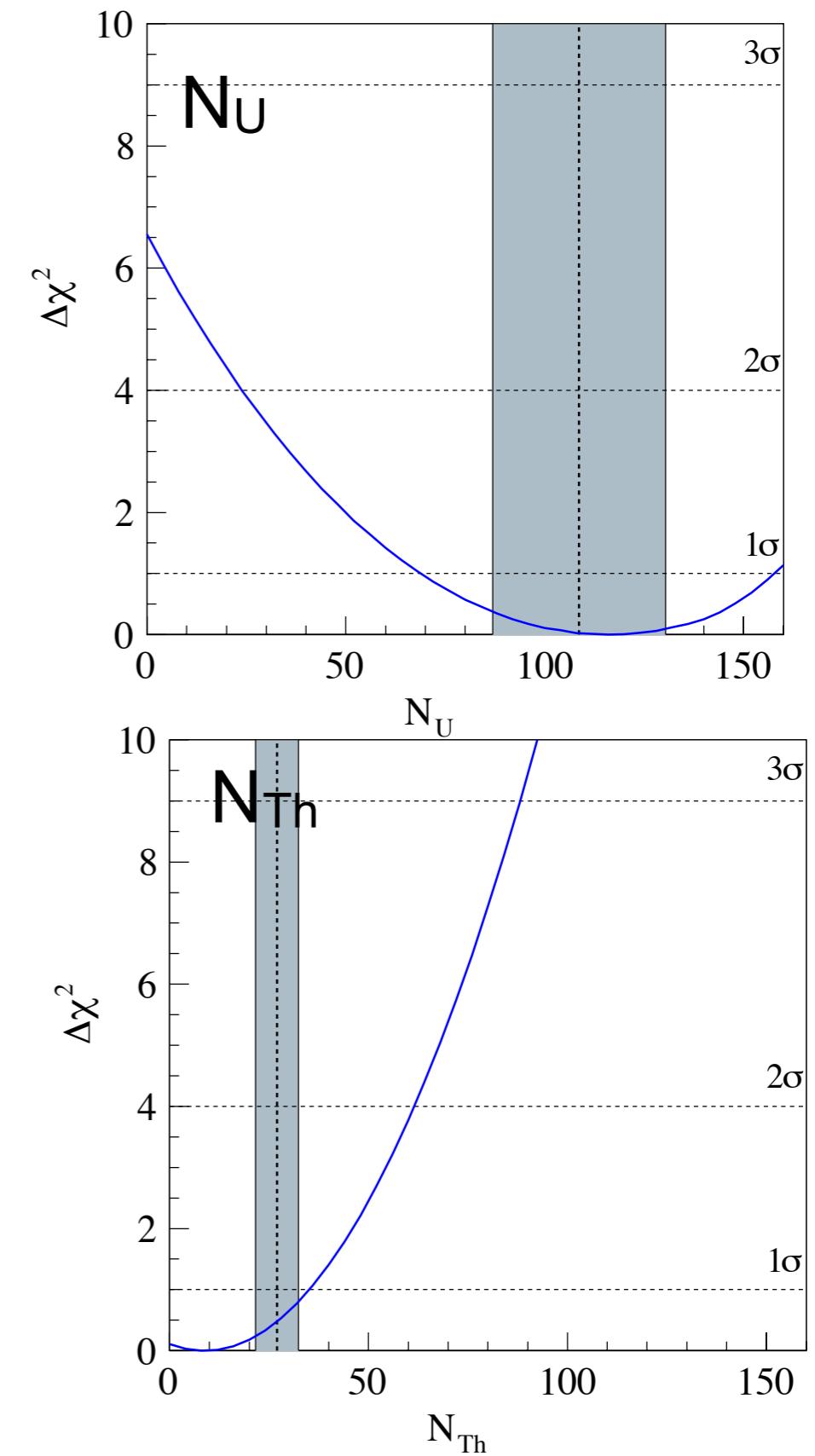
50% of the total flux originates within 500 km

N_U vs N_{Th}

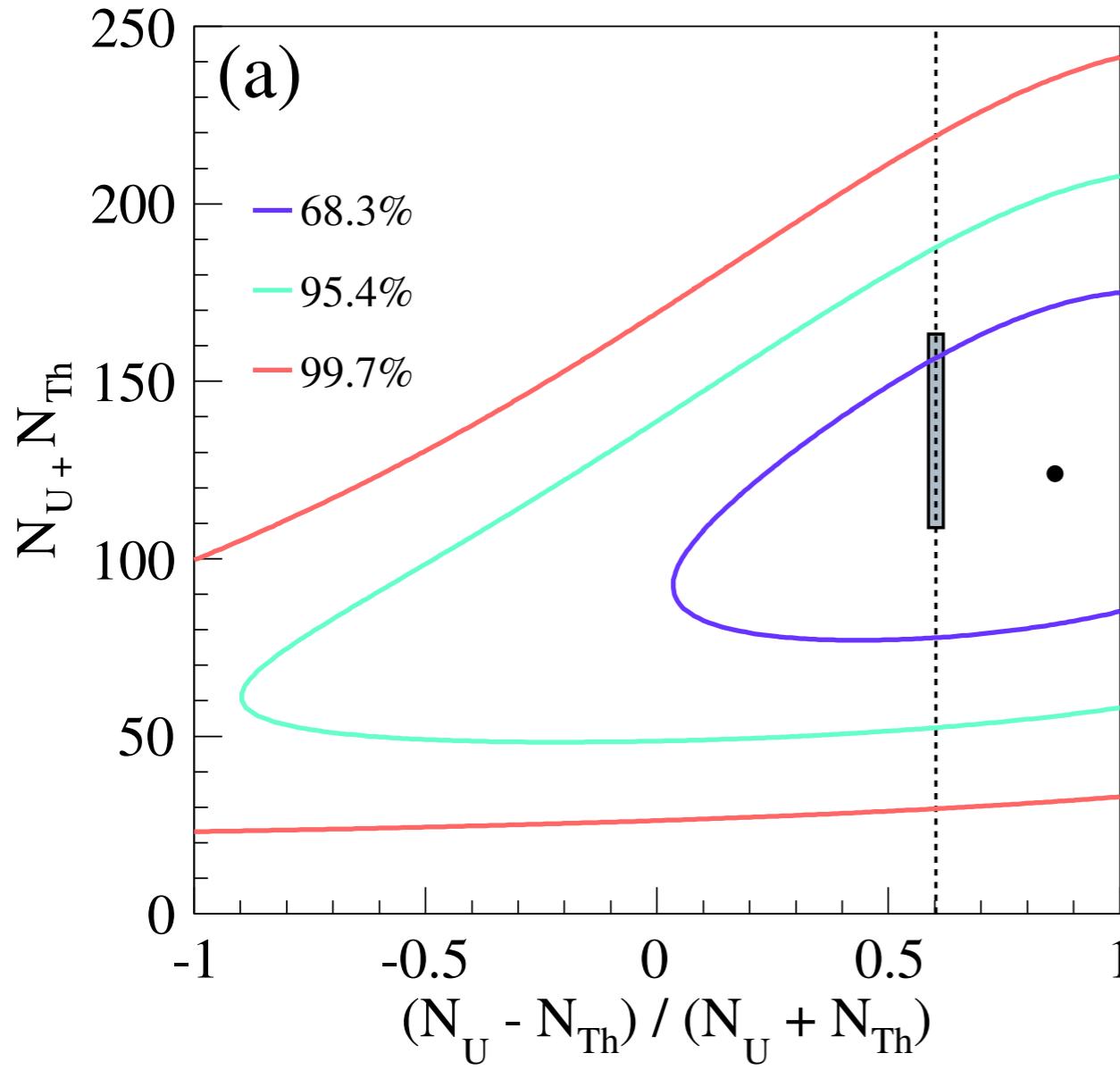


best-fit $(N_U, N_{Th}) = (116, 8)$

N_U 0 signal : rejected at 2.6σ (99.0%)



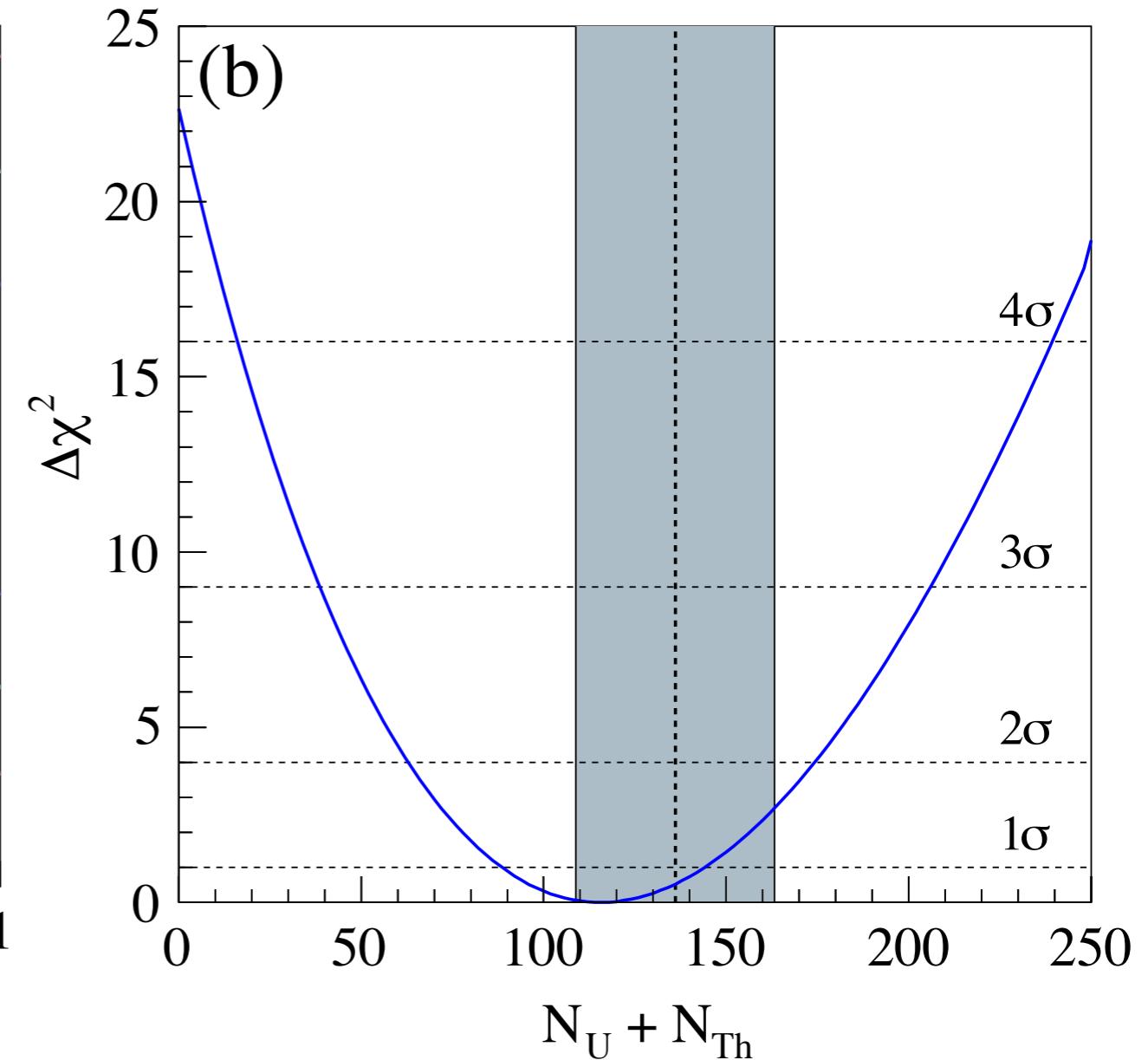
$N_U + N_{Th}$



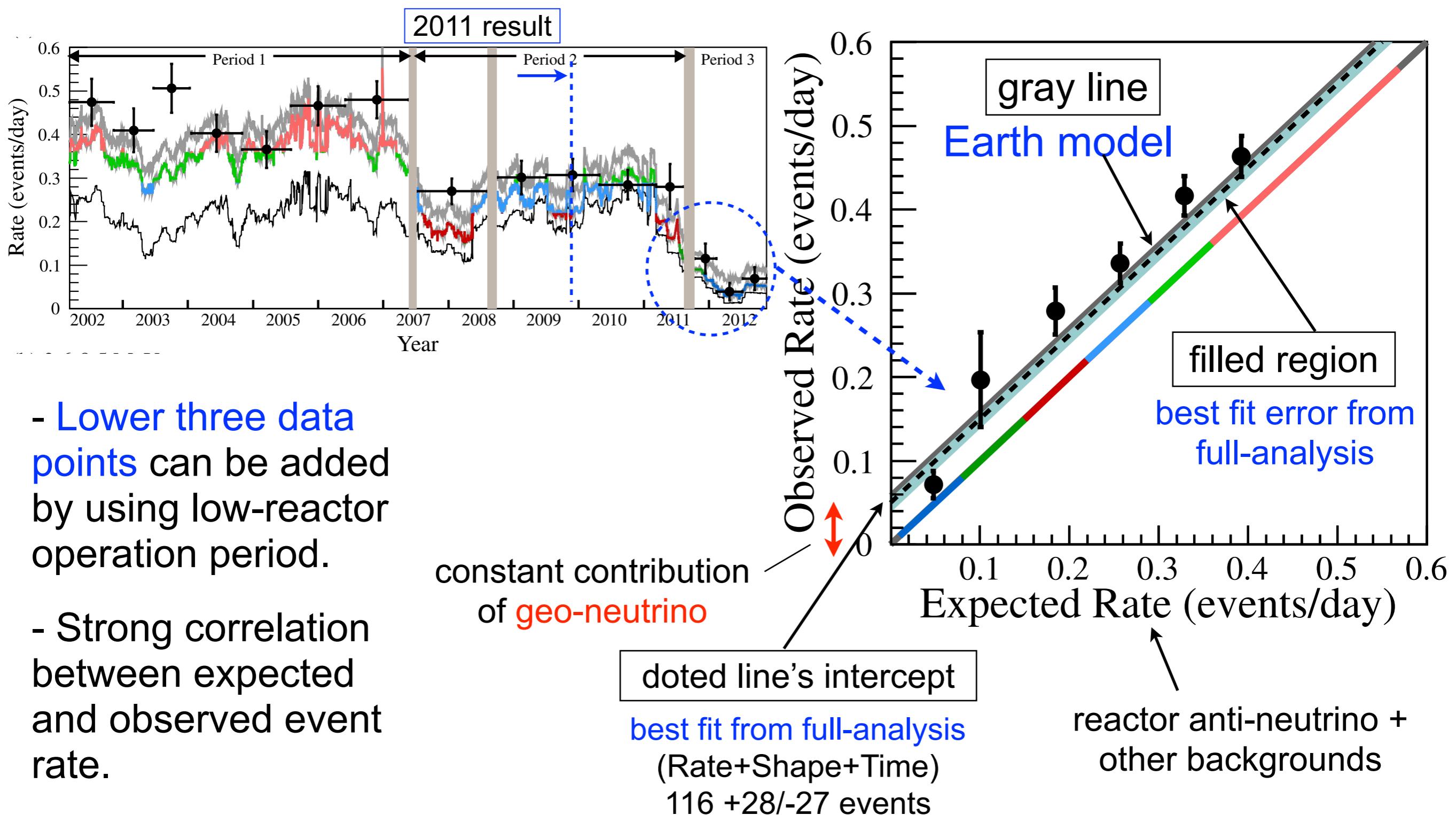
best-fit $N_U + N_{Th} = 116^{+28}_{-27}$

Flux: $3.4^{+0.8}_{-0.8} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$

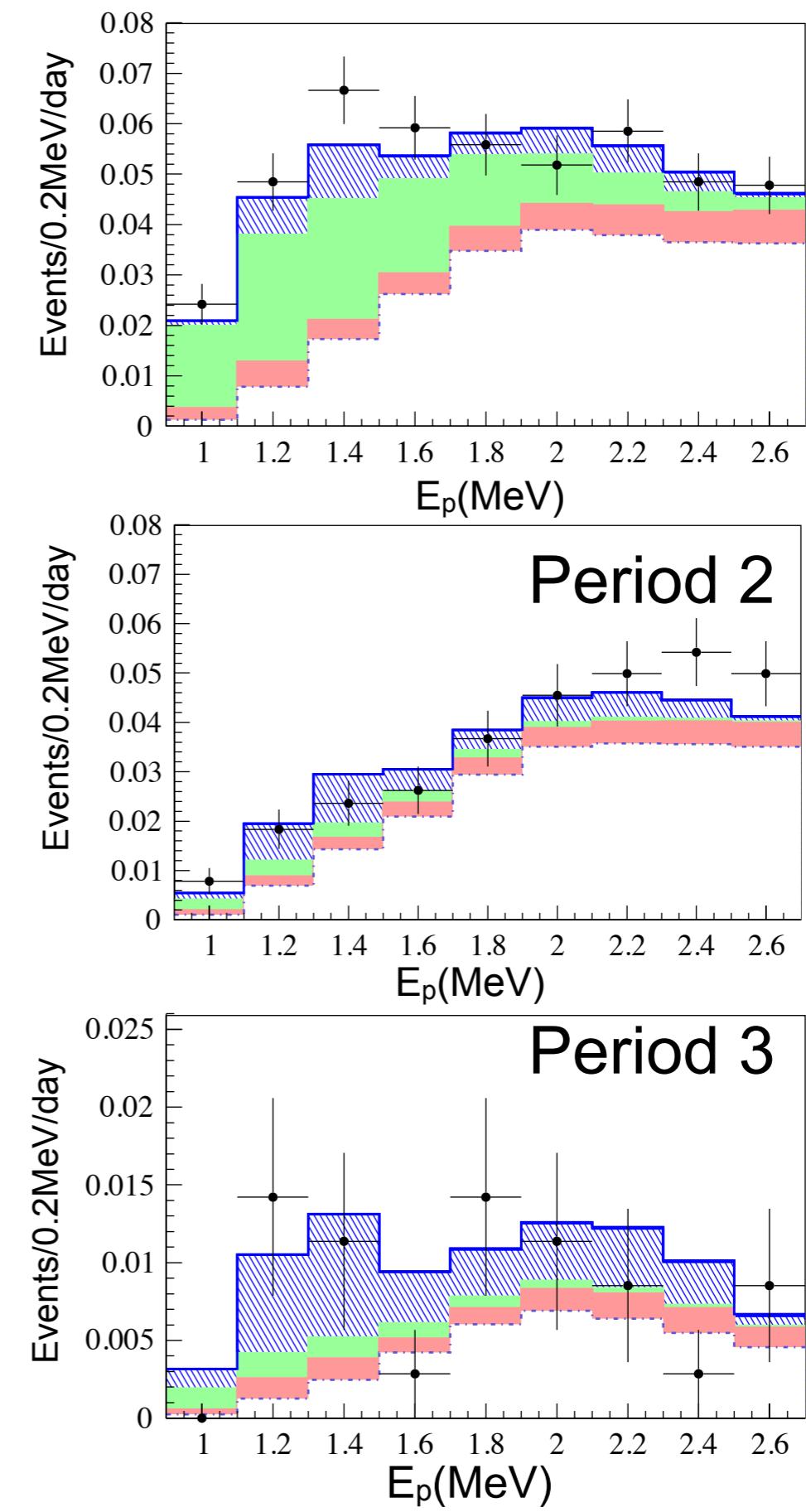
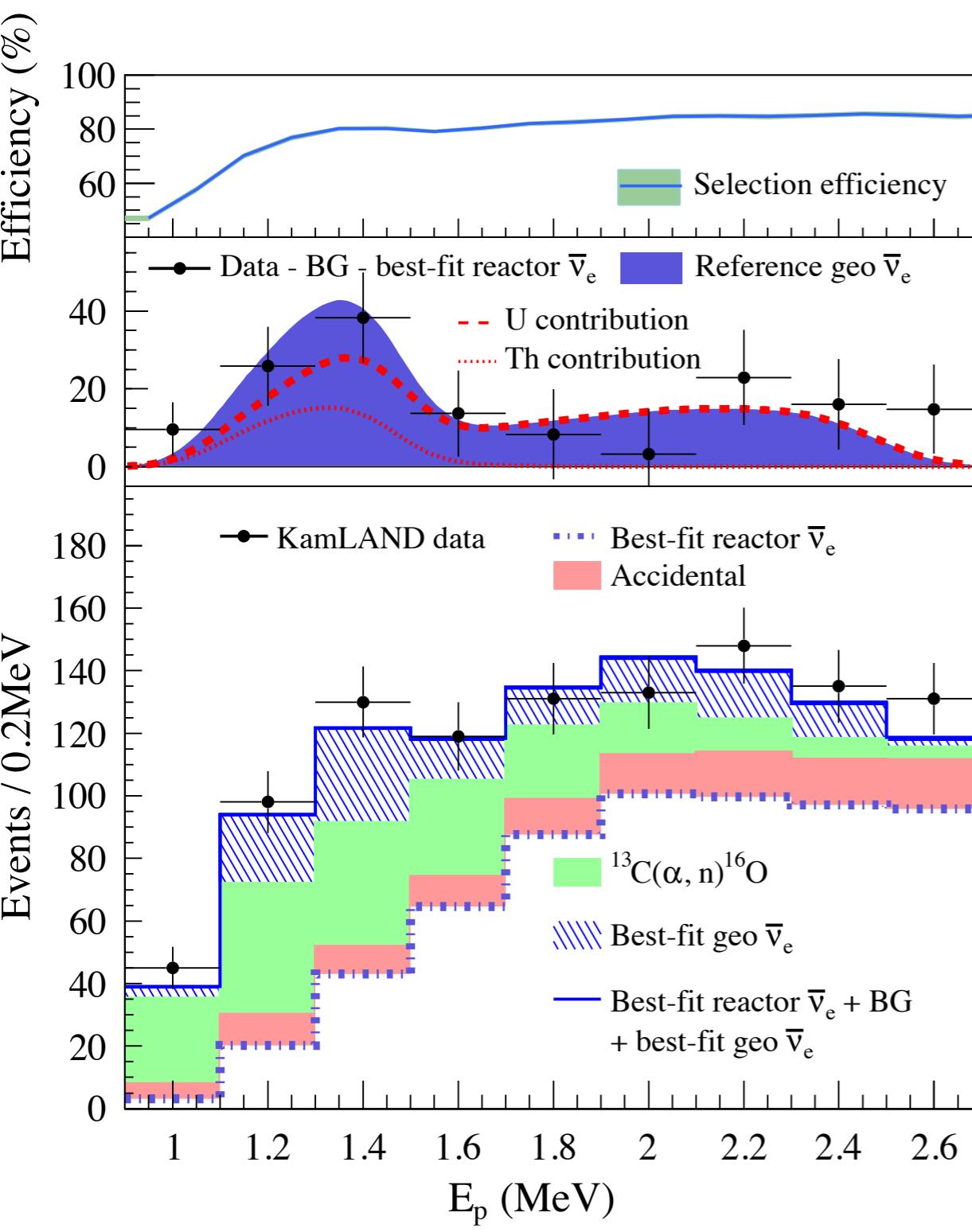
0 signal rejected at 99.9998% C.L. (2×10^{-6})



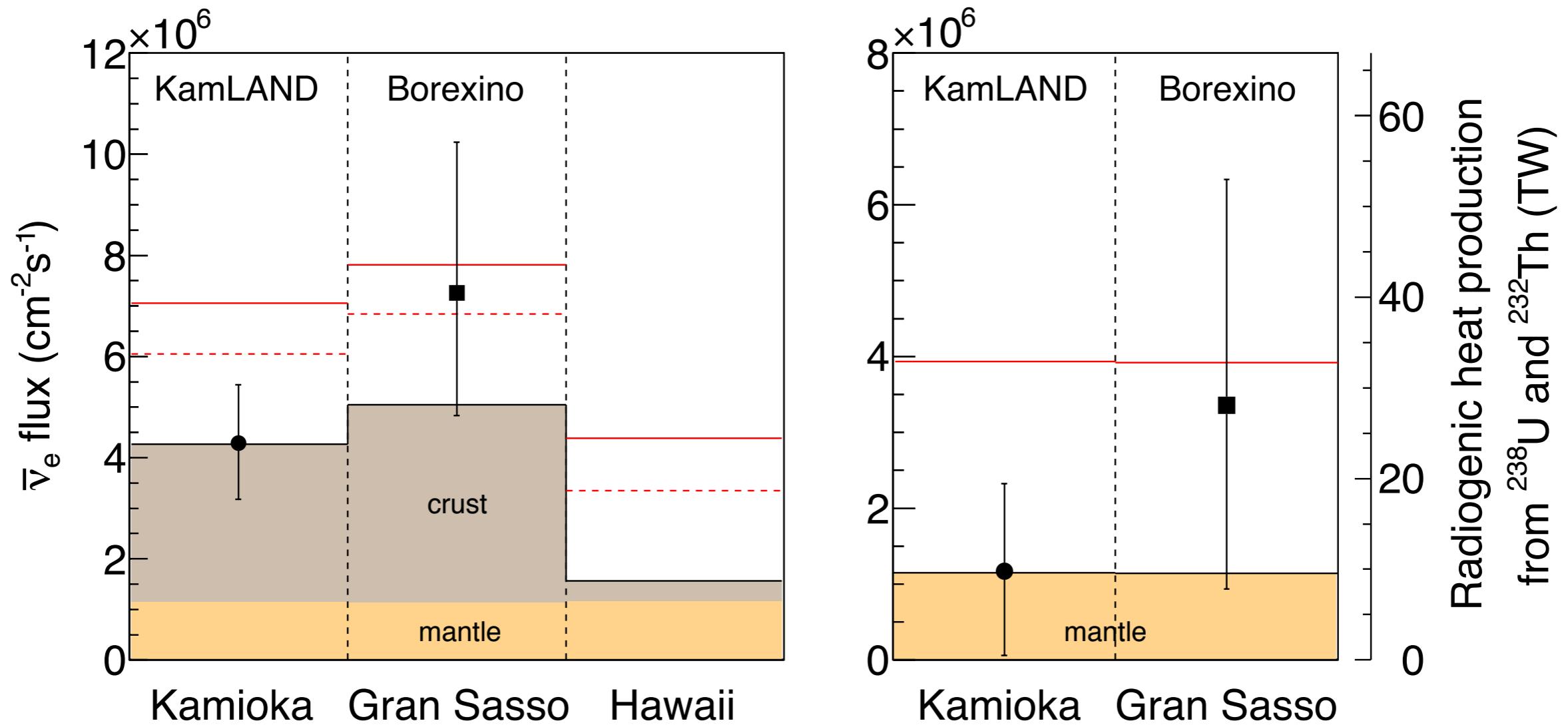
- Expected Rate vs Observed Rate (0.9-2.6 MeV)



- Lower three data points can be added by using low-reactor operation period.
- Strong correlation between expected and observed event rate.



Test of Fully-Radiogenic Model

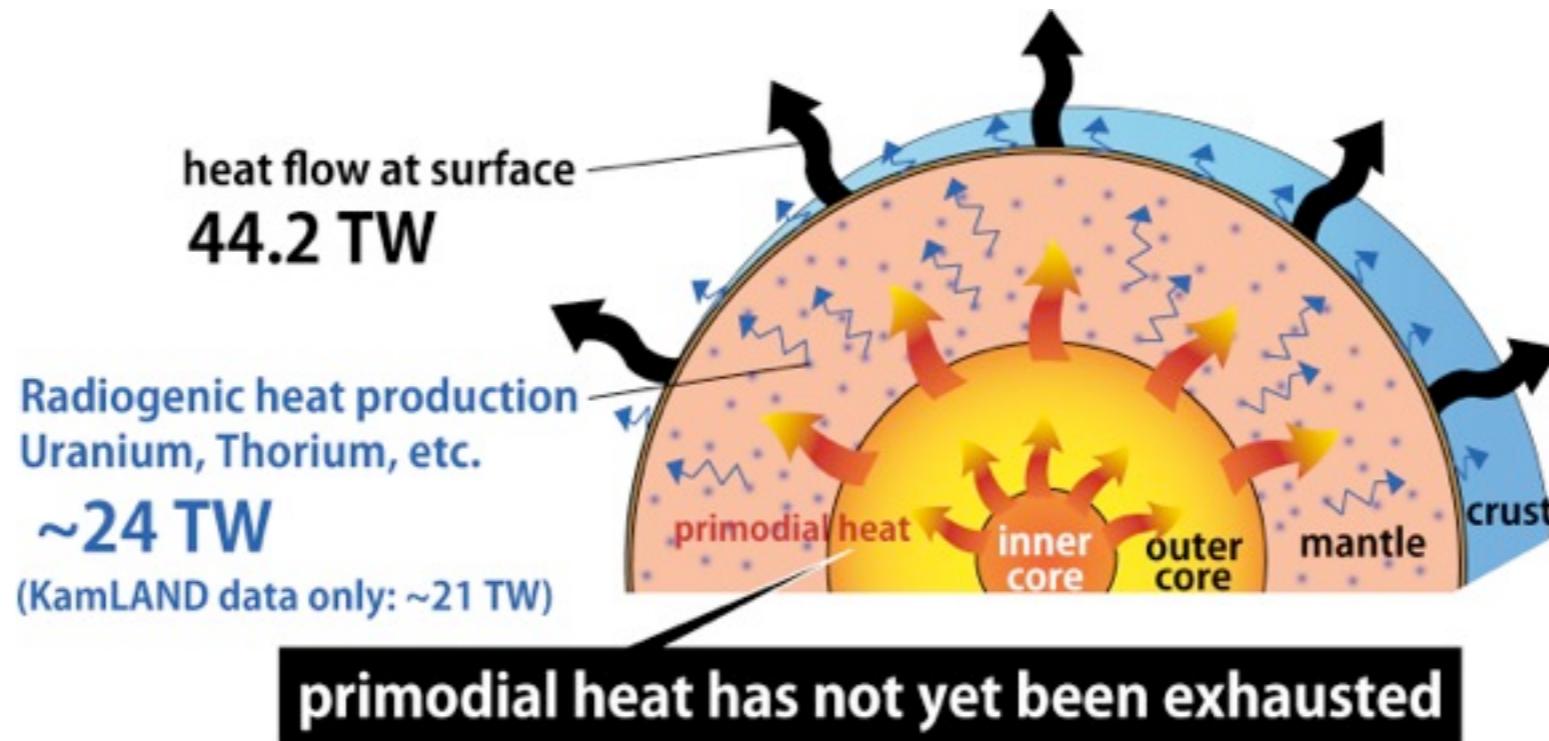


- Radiogenic heat production from ^{238}U and ^{232}Th is $20.0^{+8.8}_{-8.6}$ TW
- **Fully-radiogenic models** are disfavored at

KamLAND only **98.1% C.L.** KamLAND + Borexino **97.2% C.L.**

Measured Heat Balance

Result from geo neutrino experiment



“heat flow at surface: 44.2 ± 1.0 TW” – “radiogenic heat production: $24.3^{+8.8}_{-8.6}$ TW”

→ **primordial heat when the Earth formed**

- Geo neutrino data showed radiogenic heat ~ 24 TW contributes only half of Earth's total outgoing heat flux
- Geo reactor at the center of the Earth is constrained

KamLAND	< 5.2 TW (90% C.L.)
Borexino	< 3 TW (95% C.L.)